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METHODOLOGY FOR DETERMINING FUEL EFFECTS ON DIESEL PARTICULATE EMISSIONS

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16. ABSTRACT

To develop a methodology for characterizing particulate emissions from diesel engines, one 2-stroke cycle engine and one 4-stroke cycle engine were operated in both individual steady-state modes and according to a variation of the 13-mode diesel emissions measurement procedure. Both engines were operated on three fuel types, each of which was used with one of two available diesel fuel additives as well as by itself.

The primary particulate sampling technique employed was a dilution tunnel; and secondary evaluation techniques included a diluter-sampler developed under contract to EPA by another organization, a light extinction smokemeter, and a filter-type sampling smokemeter. Gaseous emissions were also measured, providing a running check on engine conditon.

Particulate mass rates were calculated from gravimetric data; and analysis of particulate included determination of sulfur, carbon, hydrogen, nitrogen, phenols, nitrosamines, trace metals, and organic solubles. Analysis of the organic soluble fraction included NMR, IR, paraffin boiling point distribution, benz(a)-pyrene, sulfur, carbon, hydrogen, nitrogen, and oxygen.

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March 1975

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FOREWORD

The work described in this report was performed by Southwest Research Institute for the U. S. Environmental Protection Agency under Contract No. 68-02-1230, "Development of a Methodology for Determination of the Effects of Diesel Fuel and Fuel Additives on Particulate Emissions." The project grew out of Request for Proposal No. DU-73-B428 and Southwest Research Institute's responding proposal No. 11-9366, dated March 20, 1973. The project was begun on June 23, 1973, and the technical effort was finished on February 22, 1975. It was identified within SwRI as Project No. 11-3718.

Project leader for SwRI has been Charles T. Hare, Manager, Advanced Technology, Department of Emissions Research. Overall supervision has been provided by Karl J. Springer, Director, Department of Emissions Research. Project Officer for the Environmental Protection Agency has been Dr. Ronald L. Bradow, Chief, Emissions Testing and Characterization Section, Chemistry and Physics Laboratory.

ABSTRACT

Techniques and equipment for measurement of particulate in diesel exhaust have been developed and applied, resulting in evaluations of the several methods regarding accuracy, reproducibility, and applicability to quantitative particulate testing. These techniques include a dilution tunnel with two separate sampling systems, a portable diluter-sampler developed under another EPA contract, a full-flow light extinction smokemeter, and a sampling smokemeter with later reading of filter reflectance.

Test engines used in the development and demonstration of particulate measurement procedures were a Detroit Diesel 6L-71T and a Cummins NTC-290. Both engines were turbocharged and exhibited very low smoke emissions (perhaps lower than those of a typical naturally-aspirated engine used in the urban environment). The engines were operated on three base fuels which covered a range of densities, sulfur contents, and percentages of aromatics. They were also operated on each fuel with one of two possible additives, a primary hexyl nitrate "ignition accelerator" or an organo-metallic smoke suppressant.

Emissions analysis included gravimetric measurement of particulate, and further analysis of particulate material for trace metals, sulfur, carbon, hydrogen, nitrogen, phenols, and nitrosamines. Organic solubles were extracted from the particulate and measured gravimetrically, then analyzed for BaP, NMR and IR spectra, paraffin boiling point distribution, sulfur, carbon, hydrogen, nitrogen, and oxygen. Gaseous emissions and smoke were also measured. Engine operating conditions included both steady-states and a composite of speeds and loads computed to simulate the Federal 13-mode gaseous emissions test.

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SUMMARY AND CONCLUSIONS

The objectives of this project, which were to develop and demonstrate a methodology for evaluating fuel and additive effects on diesel particulate, have been achieved. In addition, some of the data acquired during the demonstration phase can serve as characterization of the engines tested, although the data on the NTC-290 will serve this latter purpose much better than those on the 6L-71T.

Development of the methodology included calculation procedures for relating particulate acquired to total particulate emitted by the engine, sizing and calibration of sampling devices, and calculation procedures for proper weighting of modes to simulate the Federal 13-mode gaseous emissions test. This development also included quality check procedures and programs for data reduction. On the analytical side, the methodology development included refinement of BaP analysis procedures, development of procedures for determination of phenols and nitrosamines in particulate, and construction of a precision weighing chamber with controlled temperature and humidity.

The methodology demonstration included a number of test runs on each engine, with a total of over 1100 filter samples being collected. Statistical analysis on the data was limited to basics, since the contract did not allow for a large analysis effort.

A number of conclusions have been reached as a result of this research project, and the most important ones are:

1. Due to the value of results obtained in the methodology demonstration part of this project, it is recommended that the following types of analysis be performed in future research on a more or less routine basis: S, C, H, and N in particulate; total particulate mass; total organic solubles; S, C, H, N, and O in organic solubles; BaP; metals; boiling point distribution of solubles and paraffin fractions; NMR and IR analysis (limited); phenols (if a more acceptable technique can be worked out); and smoke by the PHS smokemeter.

2. Due to the lack of value of results obtained thus far, it is recommended that the following types of analysis not be performed in future research unless a special need exists: nitrosamines (not found at the limits of detection used in this project); Bosch smoke number (superfluous when PHS numbers obtained); and total particulate by ERC sampler (less accurate and more complicated than tunnel measurements).

3. The dilution tunnel technique, with proper attention to calibration and sizing of all flow systems, seems to be accurate and repeatable for determining particulate mass rates (and consequently mass rates of particulate constituents). This technique is recommended as the reference method for future studies of diesel particulate, including both large engines (where a fraction of the exhaust is diluted) and automotive-size engines (where all the exhaust can be diluted).

4. Specific particulate emission rates (g particulate per kilogram fuel consumed) were strongly influenced by fuel type and by the presence of the organo-metallic smoke-suppressant additive. Using data from the NTC-290 engine as an example (fuel-to-fuel comparisons are held to be more valid for this engine), the following observations have been made:

   (a) Average fuel specific particulate emissions using fuel "B+ additive" were higher than those using fuel "B" for all 11 steady-state conditions and the composite run.

   (b) Average fuel specific particulate emissions using fuel "C+ additive" were higher than those using fuel "C" for all 11 steady-state conditions and the composite run.

   (c) Average fuel specific particulate emissions using fuel "B" were higher than those using fuel "C" for all 11 steady-state conditions and the composite run.

   (d) Average fuel specific particulate emissions using fuel "C" were higher than those using fuel "A" for 9 of 11 steady-state conditions (plus one tie) and the composite run.

   The same general trends were in evidence for the 6L-71T engine, although not as clearly. These results are shown below (same comparisons as parts a through d):

   (e) B+ higher than B: 10 of 11 + composite
   (f) C+ higher than C: 10 of 11 + composite
   (g) B higher than C: 10 of 11 (+ one tie) + composite
   (h) C higher than A: 7 of 11

5. As a general trend, particulate mass emission rate from both engines increased with increasing power output at steady speeds. Average ranges at steady-state conditions were approximately 30 g/hr to 150 g/hr for the Detroit Diesel-Allison 6L-71T engine and 10 g/hr to 70 g/hr for the Cummins NTC-290 engine.

6. Particulates from the 6L-71T engine were indicative of a hydrocarbon-type material with a small amount of excess carbon or soot (17 percent), while those from the NTC-290 were indicative of a hydrocarbon material with a great deal of excess carbon (160 percent). These figures were determined from elemental analyses conducted by a commercial laboratory.

7. As averages for fuels not containing additives, 50 percent of particulate weight could be extracted as solubles from samples run on the 6L-71T as compared to 9 percent of particulate weight from samples run on the NTC-290. This result lends confirmation to the observation that the Detroit Diesel's particulate seemed more oily than that from the Cummins engine.

8. Elemental composition of the organic solubles obtained by commercial laboratory combustion analysis indicates a primarily hydrocarbon material with relatively small fractions of nitrogen, sulfur, and oxygen.

9. Boiling point distributions of the organic soluble fractions of particulate from the 6L-71T engine confirm that a great deal of the material boils in the same range as lubricating oil. Similar data from tests on the NTC-290 confirm that most of the solubles from that engine boil in a higher range.

10. Metals in the fuel (as in the form of an organo-metallic additive) can be reconstituted in the particulate with reasonable accuracy by X-ray analysis of particulate samples.

11. Fuel specific BaP emissions during composite runs averaged about 0.68 mg BaP/kg fuel for the 6L-71T engine and 0.21 mg BaP/kg fuel for the NTC-290. In brake specific terms, these values amount to 180 μg/kW hr (130 μg/hp hr) for the 6L-71T and 59 μg/kW hr (44 μg/hp hr) for the NTC-290. These results have been checked carefully, but they are much higher than those reported earlier by others and thus must be treated with caution.

12. As a general trend, but with a great deal of variability, smoke density from both engines increased with increasing power output at steady speeds (although baseline levels were very low for both engines). Average ranges at steady-state conditions were approximately 0.2 to 2.4 percent opacity for the Detroit Diesel-Allison 6L-71T engine and 0.5 to 2.2 percent opacity for the Cummins NTC-290 engine.

13. Major gaseous emissions as measured on the Federal 13-mode test (HC, CO, and NO_x) did not appear to be strongly influenced by fuel type or the presence of additives.

14. Compared to runs on untreated fuel, runs with the organometallic additive (used in fuels B+ and C+) had significantly lower visible smoke. This trend was reversed for total particulate mass emissions, however, with values for fuels B+ and C+ being consistently higher than for fuels B and C, respectively.

I. INTRODUCTION

Section 211 of the Clean Air Act(1)* requires the Administrator of EPA to register all fuels and fuel additives used in interstate commerce, and to require that the additive manufacturers document additive effects on gaseous and particulate emissions, control system performance, and visibility. This project was initiated to develop methods for the sampling and analysis of diesel particulate, so that the effects of fuel and additive composition could be identified. Research and development efforts were centered on three major areas, namely:

development of sampling and measurement procedures for the reproducible determination of diesel particulate mass emissions;

development of analytical procedures for identification of potentially harmful substances in particulate matter; and

demonstration of the sampling and analysis methodology using six fuels (or fuel-additive combinations) in both a 4-stroke cycle diesel engine and 2-stroke cycle diesel engine.

The approaches used in this research project resulted from the collective experience of the contractor, EPA, and others involved in air pollution studies with diesels. Particulate sampling via dilution tunnel as the reference technique came from both the literature(2-4) and the direct experience of EPA personnel. The systems used to extract isokinetic samples from the tunnel were suggested by EPA, but a great deal of effort went into sizing them, calibrating them, and refining their physical construction to the extent that they became accurate and dependable. Visible smoke measurements were conducted with the PHS opacity meter and the Bosch sampling spotmeter due to long experience with both techniques and their widespread use. Yet another measure of particulate mass was provided by using a portable sampler-diluter built by Environmental Research Corporation for EPA under contract. An evaluation of this unit was conducted concurrently with the data-taking operation.

Some of the analytical techniques applied to diesel particulate and/or the organic soluble fraction of diesel particulate had been quite well developed prior to this research project. These well-developed techniques include those for analysis of sulfur, carbon, hydrogen, nitrogen, oxygen, trace metals, boiling point distribution of organic solubles, and NMR and IR spectra. A procedure for analysis of BaP was available from the ambient air literature, but it had not been applied to the solubles in diesel particulate. Consequently, a considerable amount of development work had to be done for this application. New techniques were developed essentially from scratch for analysis of phenols and nitrosamines in particulate. No success was achieved in developing a procedure for organic peroxide analysis. Gaseous emissions and smoke were measured by well-accepted instrumentation and procedures.

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*Superscript numbers in parentheses designate references at end of report.

The engines used in the methodology development and in its demonstration were a Detroit Diesel 6L71-T turbocharged 2-stroke cycle engine and a Cummins NTC-290 turbocharged 4-stroke cycle engine. Both engines had comparatively low smoke characteristics and were somewhat more representative of engines used for intercity hauling than urban or suburban service. All the fuels used were special blends, not very similar to pump fuels which would be available for commercial use. They included a No. 1 kerosene-type fuel (with and without a primary hexyl nitrate "cetane improver"); a midrange fuel, considering aromatic content, sulfur, and density as criteria (with and without an organo-metallic smoke suppressant); and a No. 2 diesel smoke test fuel (also used with and without the smoke suppressant).

II. ENGINES, FUELS, AND ADDITIVES

The engines used to generate exhaust samples for this study were a Detroit Diesel 6L-71T and a Cummins NTC-290, both chosen by the Project Officer. A summary of the pertinent design and operating data for each engine is given in Table 1, and while a number of differences exist, the most important difference for the particulate work is probably in the operating cycle (2-stroke vs 4-stroke). This characteristic appears to have had a strong influence on the character of the particulate emitted, and it probably has an influence on the mass rate of particulate emitted as well. Photographs of the test engines are shown in Figures 1 and 2 (Detroit Diesel and Cummins, respectively). Both engines were operated in a test cell adjacent to the particulate tunnel, and the Detroit Diesel was used for all the initial setup and calibration of the sampling systems as well as for the first test (methodology demonstration) engine. The Cummins engine was used as a test engine only, once the necessary recalibrations had been performed, so it was not on the stand very long as compared to the Detroit Diesel engine.

TABLE 1. ENGINE DESIGN AND OPERATING DATA

Data item	Engine: Detroit Diesel	Engine: Cummins NTC-290
Cylinders and arrangement	I-6	I-6
Displacement, liters (in^3)	6.98 (426)	14.0 (855)
Operating cycle	2-stroke	4-stroke
Induction system	Turbocharger feeding scavenging blower	Turbocharger
Maximum boost pressure, kPa (in Hg)	67.7 (20)	47.4 (14)
Combustion chamber design	Open	Open
Fuel system	Unit injectors	High-pressure pump
Maximum power, kw (hp)	198 (265)	216 (290)
Rated rpm	2100	2100
Maximum torque, N-m (ft lb$_f$)	1044 (770)	1135 (837)
Peak torque speed, rpm	1600	1500
Manufacturer's "intermediate" speed for certification, rpm	1600	1500

These two engines were both "low smoke" types, perhaps somewhat representative of newer engines used in intercity truck service. Engines used in the urban/suburban situation tend to be smaller than the test engines, and are less likely to be turbocharged. Engines like the two test units may not contribute greatly to urban particulate; and it is difficult to say at this point whether smaller, non-turbocharged diesels emit similar particulate at similar rates.

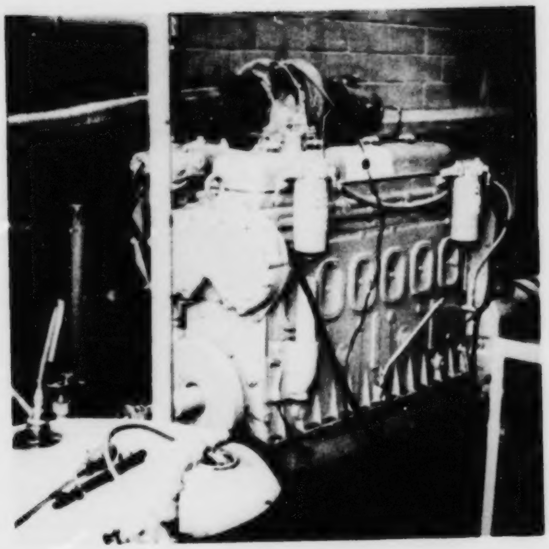

FIGURE 1. DETROIT DIESEL 6L-71T TEST ENGINE

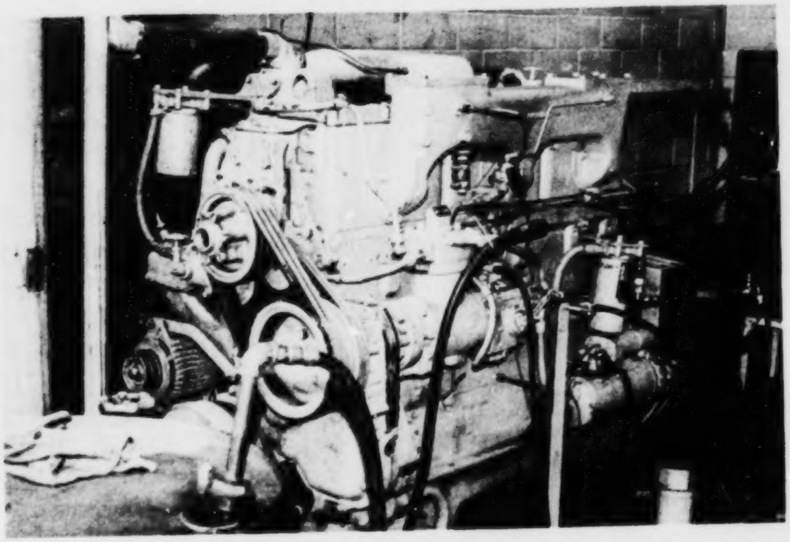

FIGURE 2. CUMMINS NTC-290 TEST ENGINE

Quite a bit of time was spent during the initial project stages in choosing the fuels and additives to be used. The major criteria were to have ranges of sulfur levels, densities, and percentages of aromatic hydrocarbons, among the fuels. Fuel B was selected to represent No. 2 diesel smoke emissions test fuel as specified in EPA regulations(5), and is considered a "worst case" fuel (high sulfur, high aromatics, high density). Fuel A is considered to be on the other end of the spectrum, with low density, sulfur, and aromatics. It is a No. 1 kerosene or DF-1 type fuel, and was expected to yield the lowest smoke.

Fuel C was selected to be between fuels A and B in density, sulfur, and aromatics. It has been referred to as a "No. 1 1/2" fuel, and due to blending it turned out to have a peculiarly truncated boiling range. Specifications for all three test fuels are presented in Table 2, and the boiling ranges are illustrated by Figure 3. Note that the simulated distillation by gas chromatograph (D2887) presents a more realistic and more accurate picture of fuel boiling range than straight distillation (D86). Figure 3 also shows the near-total absence of light ends in fuel C, and the general trend toward heavier constituents from fuel A to fuel C to fuel B.

Using the data generated by ASTM D2887, it appears that fuel A spans hydrocarbons from about C_9 to C_{17} (median around C_{12}). Fuel C appears to include materials from about C_{11} to C_{21} (median around C_{13}), and fuel B contains hydrocarbons from about C_9 to C_{26} (median around C_{15}). Distillation by D86 and simulated distillation by D2887 were conducted on all three of the "fuel + additive" combinations also, but the results were so nearly identical to those for the fuels alone that it is not worthwhile to discuss them here.

The test fuels do not necessarily represent fuels used in normal vehicle operation, and they were not intended to do so. It is useful, however, to compare them to some more typical diesel fuels, because fuel composition does appear to have a significant effect on particulate emissions. A brief comparison is given in Table 3, with data on the "typical" fuels coming from the U.S. Bureau of Mines(6). Fuel A is shown to be somewhat lighter than a "typical" No. 1 fuel, and to have a much lower sulfur content. Fuels B and C bracket the "typical" No. 2 fuel in terms of boiling range, density, and sulfur content.

The additives used for methodology evaluation during this project were Ethyl DII-2 and Lubrizol 8005. The Ethyl material is a primary hexyl nitrate (organic) material intended for use as an ignition accelerator or "cetane improver". Lubrizol 8005 is an organo-metallic used as a smoke suppressant, containing calcium and a small amount of barium. Typical properties of these two materials are given in Table 4, verifying that they are physically as well as chemically dissimilar.

TABLE 2. FUELS USED FOR DIESEL PARTICULATE STUDIES

Project fuel code	A		B		C	
SwRI fuel code	EM-197-F		EM-195 & 204-F		EM-198-F	
Fuel type	No. 1 Kerosene		2D Emissions		"No. 1 1/2"	
	Boiling range by ASTM method No.					
Distillation, °C, (°F)	D86[a]	D2887[b]	D86	D2887	D86	D2887
IBP	166 (330)	148 (298)	196 (384)	161 (321)	210 (410)	191 (376)
10%	179 (354)	163 (326)	223 (434)	198 (388)	219 (426)	218 (425)
20%	182 (360)	173 (344)	238 (460)	217 (422)	227 (441)	228 (442)
30%	186 (366)	181 (357)	251 (483)	240 (464)	230 (446)	233 (452)
40%	191 (376)	195 (383)	260 (500)	257 (494)	232 (450)	237 (458)
50%	197 (387)	203 (397)	270 (518)	271 (519)	235 (455)	239 (463)
60%	206 (420)	217 (422)	277 (531)	284 (544)	238 (460)	248 (479)
70%	214 (418)	229 (445)	287 (548)	301 (573)	241 (465)	254 (490)
80%	225 (437)	238 (460)	298 (569)	316 (601)	248 (479)	261 (502)
90%	238 (460)	253 (488)	316 (601)	338 (640)	261 (502)	274 (525)
EP	274 (525)	301 (574)	356 (673)	417 (782)	312 (594)	356 (672)
% Recovery	99	----	98	----	99	----
% Residue	1	----	2	----	1	----
% Loss	0	----	0	----	0	----
Aromatics, %	9.2		35.1		23.0	
Olefins, %	0.8		0.0		1.0	
Saturates, %	90.0		64.9		76.0	
Gravity, g/ml (°API)	0.794 (46.8		0.850 (34.9)		0.828 (39.4)	
Cetane (calculated)	51.0		49.5		49.5	
Total sulfur, wt. %	0.003		0.319		0.010	
Weight %C	85.0		86.5		85.3	
Weight %H	13.9		12.8		13.9	
Weight %N	0.08		0.10		0.04	
Viscosity, cs	1.62		2.7		2.12	
Flash point, °C (°F)	54 (130)		80 (176)		85 + (185+)	

[a] thermal distillation, % by volume

[b] gas chromatograph simulated distillation, % by weight

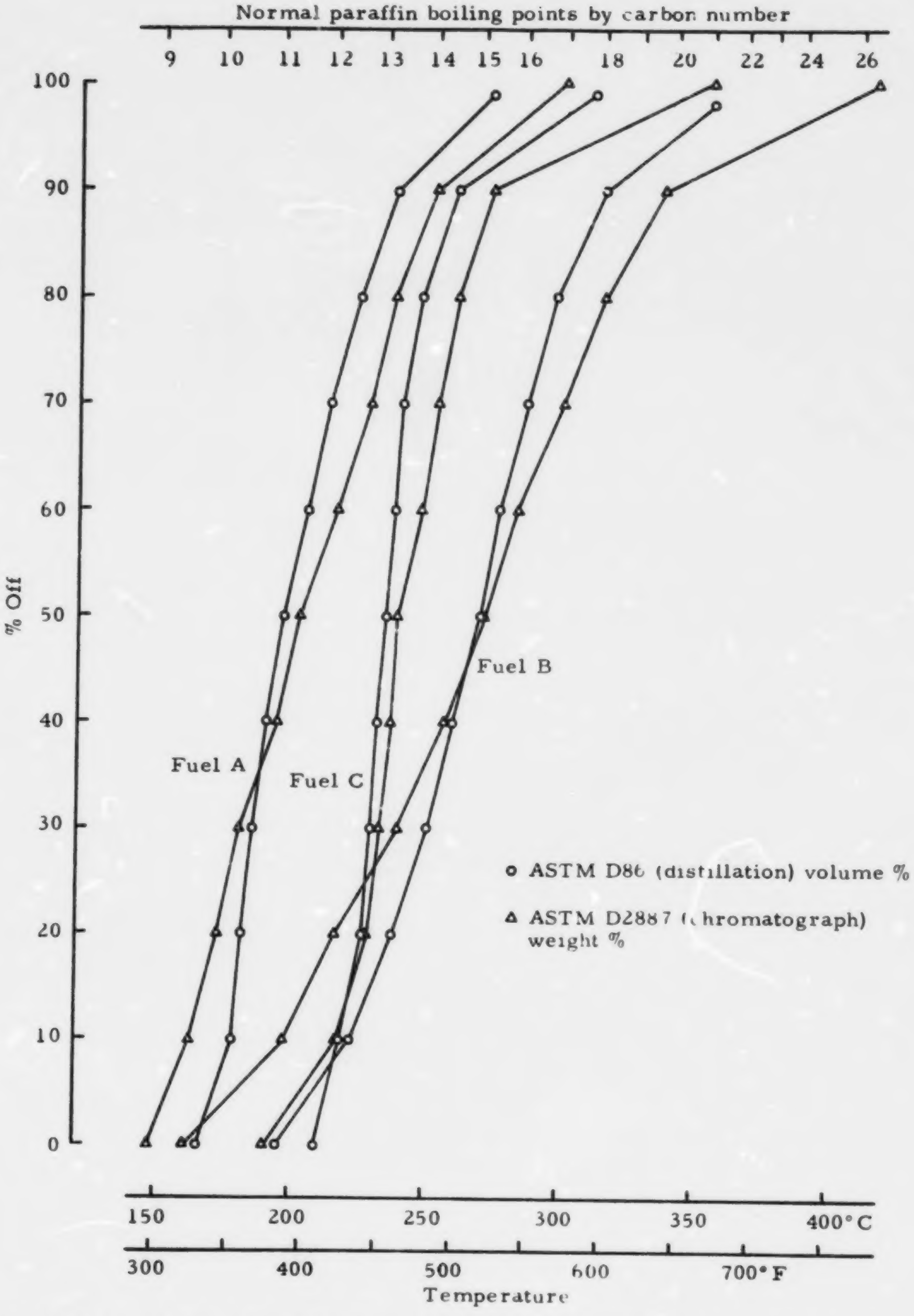

FIGURE 3. BOILING RANGES OF FUELS USED IN METHODOLOGY DEMONSTRATION

TABLE 3. COMPARISON OF TEST FUELS WITH "TYPICAL"[a] DIESEL FUELS

Fuel property	Method	Data by fuel code or type				
		A	B	C	"Typical" No. 1	"Typical" No. 2
Distillation, °C (°F)	D86					
IBP		166 (330)	196 (384)	210 (410)	177 (351)	189 (373)
10%		179 (354)	223 (434)	219 (426)	199 (391)	219 (426)
50%		197 (387)	270 (518)	235 (455)	228 (443)	257 (495)
90%		238 (460)	316 (601)	261 (502)	263 (505)	302 (575)
EP		274 (525)	356 (673)	312 (594)	284 (544)	327 (620)
Gravity, g/ml	D287	0.794	0.850	0.828	0.818	0.843
Gravity, °API		46.8	34.9	39.4	41.4	36.4
Total sulfur, wt. %	D129	0.003	0.319	0.010	0.096	0.228

[a]These values are averages of regional data in the 1973 Bureau of Mines Diesel Fuel Survey and are not sales-weighted

TABLE 4. TYPICAL PROPERTIES OF ADDITIVES USED FOR METHODOLOGY EVALUATION

Lubrizol 8005		Ethyl DII-2	
Property	Value	Property	Value
Density, g/ml @ 16°C	1.14	Density, g/ml @ 20°C	0.97
Viscosity, cP @ 38°C	71	Viscosity, cP @ 38°C	0.95
Flash point, °C (°F)	>93(>200)	Flash point, °C (°F)	69 (156)
Wt. percent Ca	11.4		
Wt. percent Ba	2.22		
Wt. percent S	1.0		
Wt. percent sulfated ash	42.2		

Additive treatment levels used were those indicated to be representative of field usage by the additive manufacturers, namely 0.1% by volume for DII-2 and 0.25% by volume for 8005. Composition and coding of the fuels is summarized in Table 5 for reference.

TABLE 5. CODING AND COMPOSITION OF FUELS AND FUEL-ADDITIVE MIXTURES

Fuel Name	Fuel Type	SwRI code	Additive & Vol. %
A	No. 1 kerosene	EM-197-F	None
B	2D Emissions test	EM-195-F[a]	None
C	"No. 1 1/2"	EM-198-F	None
A + additive	As above but with additives	EM-209-F	DII-2 at 0.1
B + additive		EM-210-F[b]	8005 at 0.25
C + Additive		EM-211-F	8005 at 0.25

[a] EM-204-F after 8/22/74 (new batch)
[b] EM-224-F after 8/22/74 (new batch)

Lubrizol 8005 was added to the two heavier fuels because it was assumed that they were most likely to produce high smoke levels. Although the cetane number of fuel A was adequate for satisfactory performance with either test engine, the DII-2 ignition accelerator was added to ascertain its effects, if any, on particulate mass and composition.

III. INSTRUMENTATION AND TEST EQUIPMENT

This section is included primarily as descriptive material on the hardware used to accomplish the necessary measurements, and it should provide adequate background for the technical discussions to follow. Both engines were operated on a conventional test stand which employed a 373kw (500 hp) capacity eddy-current dynamometer and a large inertia wheel. This stand did not have motoring capability (of little use with diesels), but the inertia wheel could be selectively coupled or uncoupled depending on procedural requirements.

Engine fuel flow was measured using a bridge-type mass flowmeter manufactured by Flo-Tron, Inc., which is a widely-used industrial instrument. Engine air flow was measured using a sharp-edged orifice installed downstream of an MSA Ultra-Aire filter system, and the flanges holding this orifice are visible on the vertical black duct at the left in Figure 4. Figure 4 also shows the whole dilution tunnel, which used another MSA filter for dilution air cleanup. The engine being operated for particulate collection is on the other side of the wall at left in Figure 4, and the instrument under the center of the tunnel is the chemiluminescent analyzer used for computing actual exhaust dilution.

The muffler used on these engines is shown in detail in Figure 5, with special modifications to the upper end to provide three separate exhaust outlets. The two larger outlets (with valves) permitted most of the engine's exhaust to escape to the atmosphere, but the portion in the small pipe went directly into the tunnel. To prevent an overly large amount of exhaust from going into the tunnel, restrictor tubes were constructed as shown in Figure 6. These tubes were inserted into the existing 3-inch muffler outlet on a trial-and-error basis, and they were built with the same inside length and perforation pattern as the existing tube. This technique provided more restriction between muffler and tunnel than the existing tube, but presented a passage for the exhaust which was as normal in configuration as possible.

The dilution tunnel itself was flow-calibrated in much the same way as one would calibrate a constant-volume sampler (CVS). It employs a positive-displacement rotary vane gas pump, and the calibration permitted flowrate (and thus isokinetic velocity) calculations to be made utilizing blower rotations and elapsed time. The counter and timer are shown in Figure 7 along with gauges used to measure pressure at the sampling section and across the blower. Figure 8 is a schematic section of the dilution tunnel with its important dimensions specified. This tunnel (the first one built by the contractor) was made of 3.2mm (1/8 inch) stainless steel sheet rolled into duct form and welded along a seam at the bottom. All tunnel connections were made with flanges and gaskets to insure against leaks, even though the vacuum in the tunnel was very slight (approximately

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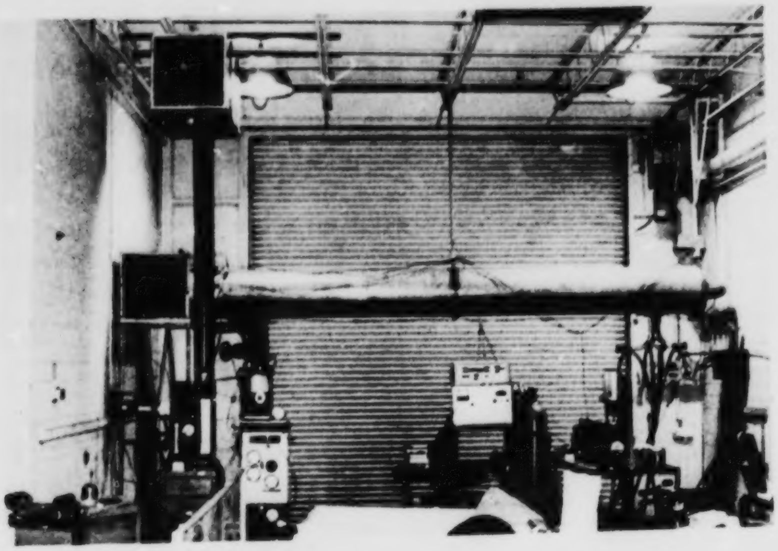

FIGURE 4. OVERALL VIEW OF DIESEL PARTICULATE DILUTION TUNNEL

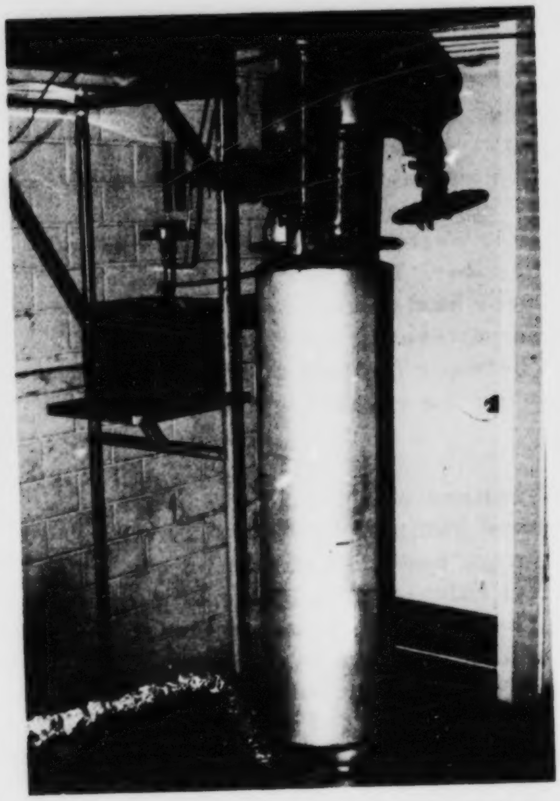

FIGURE 5. DETAIL OF EXHAUST MUFFLER USED FOR TESTING

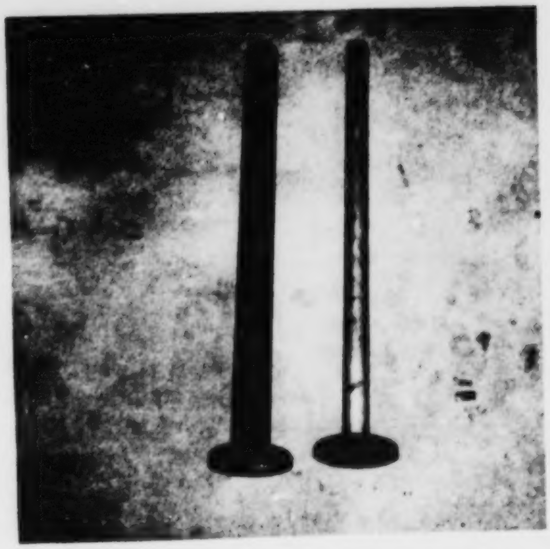

FIGURE 6. DETAIL OF PERFORATED EXHAUST RESTRICTORS USED TO LIMIT EXHAUST FLOW INTO TUNNEL

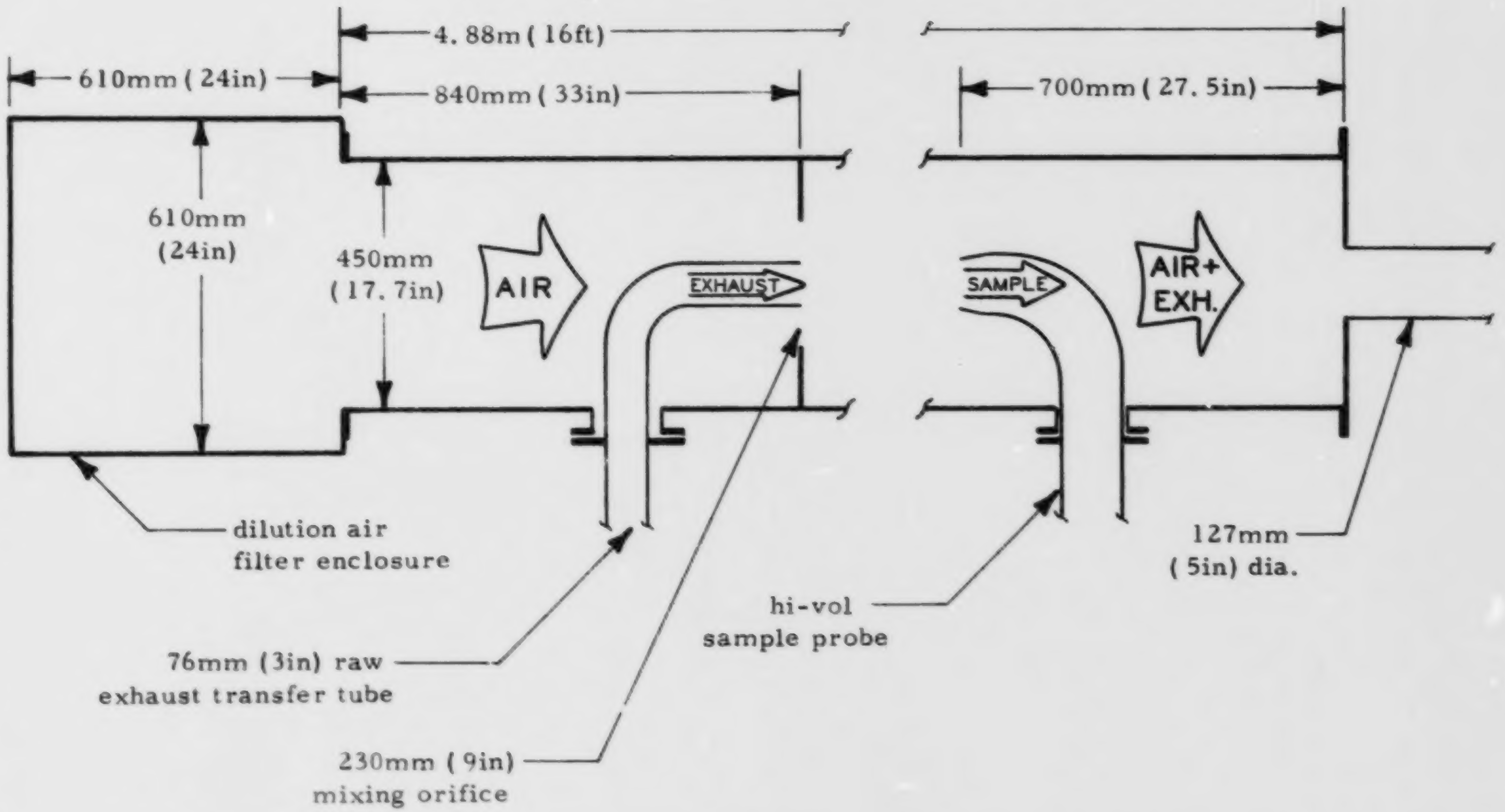
4. 88m (16ft)
610mm (24in)
840mm (33in)
700mm (27. 5in)
610mm
(24in)
450mm
(17. 7in)
AIR
EXHAUST
SAMPLE
AIR+
EXH.
dilution air
filter enclosure
76mm (3in) raw
exhaust transfer tube
230mm (9in)
mixing orifice
hi-vol
sample probe
127mm
(5in) dia.

FIGURE 8. SCHEMATIC SECTION OF DILUTION TUNNEL FOR DIESEL PARTICULATE SAMPLING

0.5 kPa or 2 inches H_2O).

Three sampling systems were used (one at a time) with the dilution tunnel for different types of filters. The "47mm" system is shown in Figures 9 and 10, and it was installed (as were all the others) with probe pointing upstream. Each of the four separate probes led to a 47mm filter case, three holding glass fiber filters and one holding a Fluoropore* filter. Flows through these systems were set and maintained using the flowmeters (with metering valves) shown in Figure 11, and flows were totalized using the dry gas meters also shown in Figure 11. Each sampling system was connected to a separate pump to prevent unwanted interactions and permit stopping sample acquisition at will to replace filters. The reducers inserted in the 25mm (1 inch) tubes shown in Figure 9 were necessary for isokinetic sampling through the small filters.

A modified "hi-vol" sampling system was used to collect samples on 203mm by 254mm (8 by 10 inch) rectangular glass fiber filters as shown in Figures 12 and 13. The sampling nozzle (Figure 12) was inside the tunnel down to the flange when operating, and the upper half of the filter holder plus the whole unit shown in Figure 13 extended downward from the tunnel. The "tailpipe" added to the hi-vol blower contained a straightening section and a sharp-edged orifice to provide for computation and monitoring of sample flow.

It became necessary during the test sequence to take some samples on large Fluoropore filters (293mm diameter), requiring a modification of the hi-vol system due to the high pressure drop of these filters. Although it is somewhat difficult to see in Figure 14, the filter holder was modified to include another gasket and a spacer which restricted the effective filtration area slightly. The "tailpipe" was sealed to prevent in-leakage, and the Roots gas pump shown in Figure 15 was connected to its lower end by tubing and mounted outside the building. Other items added were the bypass system and vacuum guage shown in Figure 16, permitting accurate orifice flow calculations and vacuum relief before the filter plugged. This system could have been used with glass fiber filters as well, but the regular hi-vol system was less complicated to operate and thus was used whereever possible.

The final particulate sampling system to be discussed withdrew samples not from the dilution tunnel, but from the exhaust pipe upstream of the muffler. This system was a portable sampler-diluter developed for the Environmental Protection Agency by Environmental Research Corporation under Contract No. 68-02-0589. It will be referred to from this point on as the "ERC sampler" for brevity. The unit is shown in Figure 17 along with the sample pump and flow measuring devices necessary for its operation,

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*Trademark of the Millipore Corporation

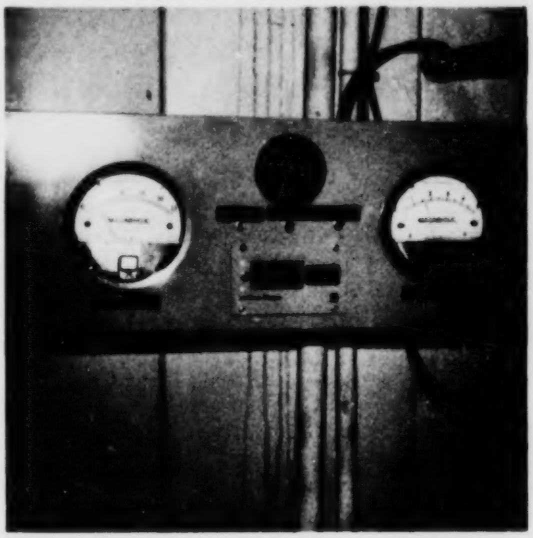

FIGURE 7. TUNNEL BLOWER COUNTER AND TIMER

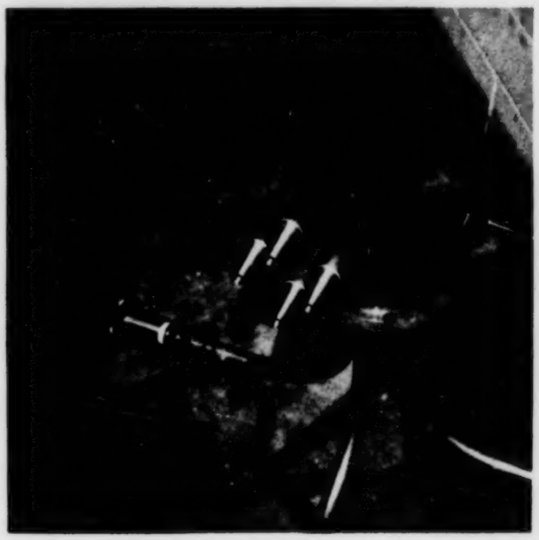

FIGURE 9. PROBES USED WITH 47mm SAMPLING SYSTEMS

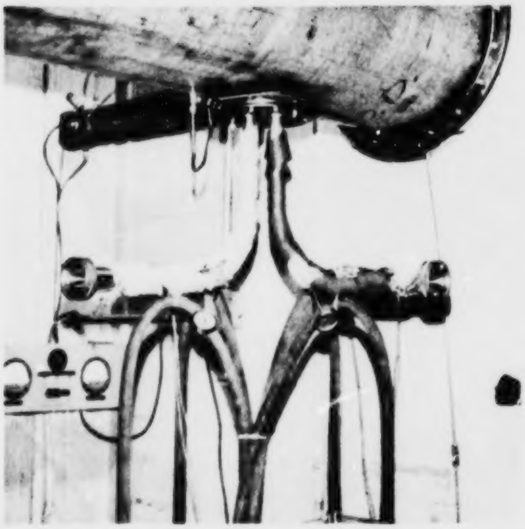

FIGURE 10. 47mm FILTER HOLDERS

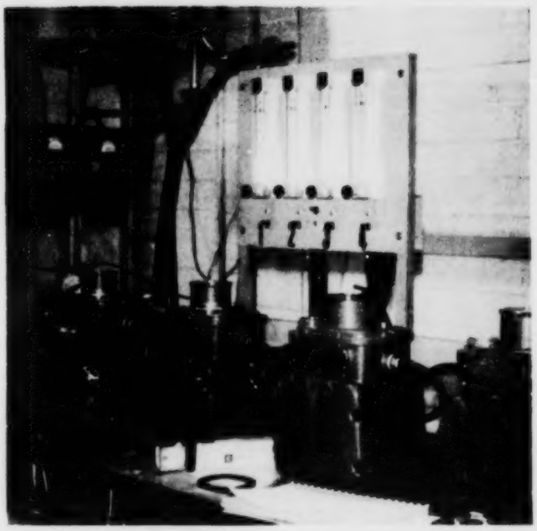

FIGURE 11. FLOWMETERS AND TOTALIZING METERS USED WITH 47mm FILTERS

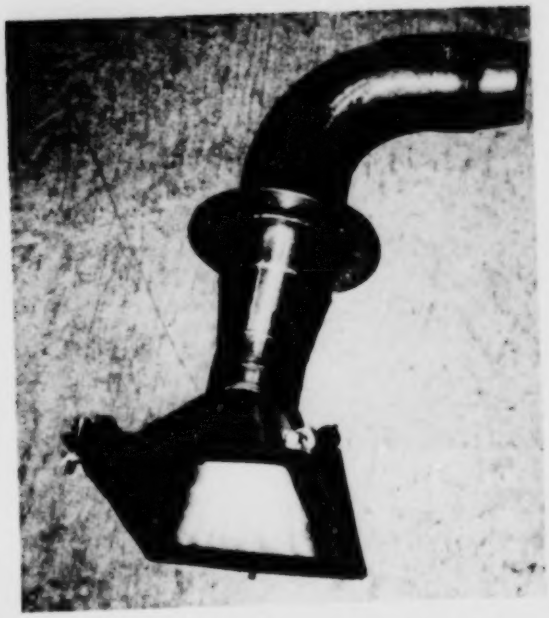

FIGURE 12. SAMPLING NOZZLE USED WITH HI-VOL SYSTEM

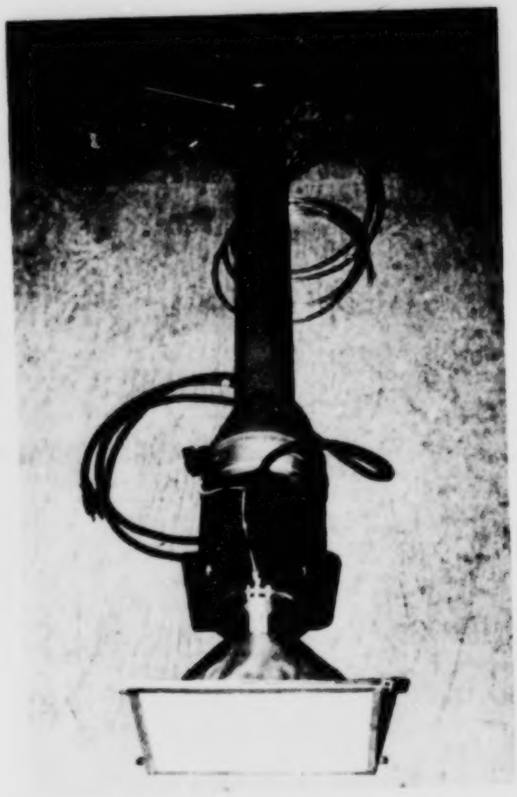

FIGURE 13. BLOWER AND FLOW MEASUREMENT APPARATUS USED WITH HI-VOL SYSTEM

FIGURE 14. MODIFIED HI-VOL SYSTEM USED WITH 293mm FLUOROPORE FILTERS

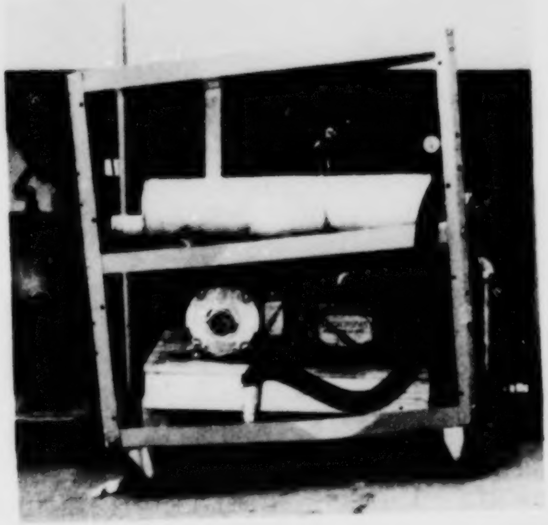

FIGURE 15. GAS PUMP USED WITH 293mm FLUOROPORE FILTERS

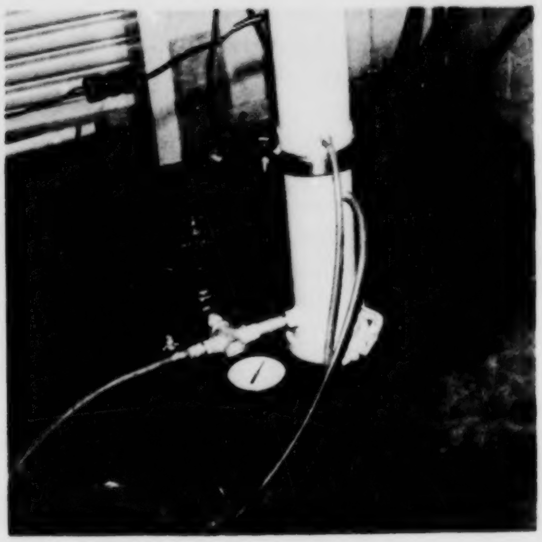

FIGURE 16. FLOW MEASUREMENT SYSTEM USED WITH 293mm FLUOROPORE FILTERS

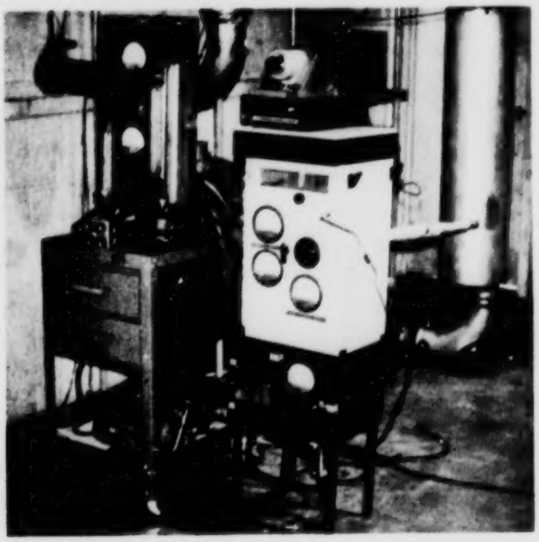

FIGURE 17. ERC SAMPLER-DILUTER

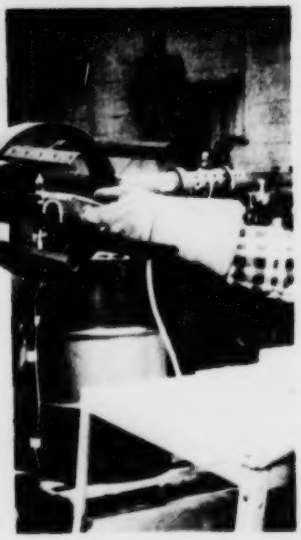

FIGURE 18. PHS SMOKEMETER AND BOSCH SAMPLING UNIT BEING EMPLOYED FOR DIESEL SMOKE MEASUREMENT

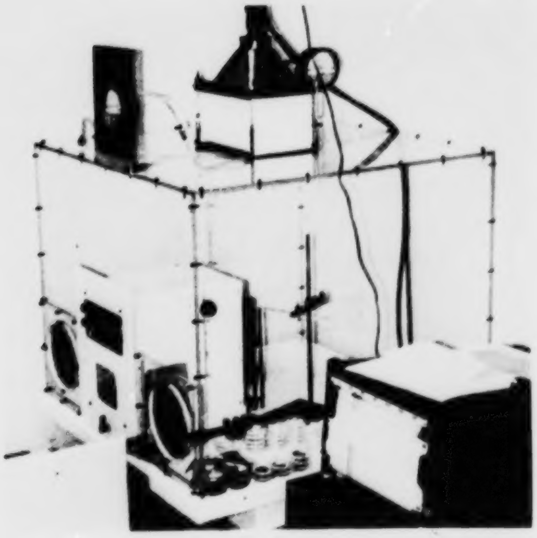

FIGURE 19. HUMIDITY - AND TEMPERATURE- CONTROLLED CHAMBER HOUSING MICROBALANCE FOR FILTER WEIGHING

but it is shown not connected to the exhaust pipe at its normal sample point. The fitting mounted at the elbow leading into the muffler held the probe for the ERC sampler when in operation, and the sample line was heated from the sampling point back to the sampler.

In order to obtain some smoke density measurements against which particulate emissions data could be compared, both the Federal (PHS) smokemeter and the Bosch sampling smokemeter were employed. These systems are shown being used in Figure 18, with the optical unit of the PHS meter mounted on the end of the stack and the Bosch probe inserted into the stack. The control and readout unit of the PHS meter was located at the engine operator's position, and the filters through which exhaust gas was sampled for the Bosch unit were later measured for reflectance.

The final major item of equipment necessary to this project was the humidity- and temperature - controlled weighing chamber and microbalance shown in Figure 19. It was made of plexiglass and equipped with a flow-through ventilation system providing filtered air controlled to ±0.6°C and ±2% relative humidity. The air system includes a chilled water spray chamber for absolute humidity control, followed by controlled electrical reheat and an MSA Ultra-Aire filter. The box is maintained at a positive pressure of 37 Pa (0.15 inch H_2O) by a blower and an outlet orifice, and total flow through the box is about 0.3 m^3/min (10 ft^3 min). The nominal conditions to which air in the box is controlled are 72°F dry bulb and 39 percent relative humidity (46 grains H_2O/lb_m dry air).

IV. PROCEDURES FOR ANALYSIS OF PARTICULATE COMPOSITION

Once the particulate matter had been collected and weighed, it was sent to one of several other laboratories for further study. Table 6 summarizes the analysis activities, with three of the five other

TABLE 6. SUMMARY OF ANALYSES FOR PARTICULATE COMPOSITION

Sample form	Laboratory	Analysis for	Method	Output
Particulate on 47mm glass fiber filters	Galbraith[a]	Carbon, hydrogen, nitrogen, sulfur	Combustion	Data only
Particulate on 47mm Fluoropore filters	S. E. A. L.[b]	Metals (Ca, V, Mn, Ni, Cu, Zn, Pb, Sr, Sn, Ba)	X-ray fluorescence	Data only
Particulate on 293mm Fluoropore filters	SwRI Dept. 1[c]	Phenols, nitrosamines	Extraction and G. C.	Data only
Particulate on 8 x 10 glass fiber filters	SFRE[d]	Total organic solubles; NRM, IR, and BaP in organic solubles	Soxhlet extraction plus spectral analysis or TLC and fluorescence spectrophotometry	Data and remaining organic solubles
Organic solubles	Galbraith[a]	Carbon, hydrogen, nitrogen, fulfur and oxygen	Combustion	Data only
	SwRI Dept. 10[e]	Boiling point distribution of paraffins in organic solubles	Fractionaction and GC analysis	Data only

[a] Galbraith Laboratories, Inc., Knoxville
[b] Scanning Electron Analysis Laboratories, Inc., Los Angeles
[c] Department of Chemistry and Chemical Engineering
[d] Southwest Foundation for Research and Education
[e] U. S. Army Fuels and Lubricants Research Laboratory

laboratories being located within the Southwest Research Center complex. Most of the analyses desired under the subject contract were performed with good results, but no success was achieved in developing a method for analysis of organic peroxides. It was felt that effort needed on procedural development of the phenol and nitrosamine analyses would be compromised if the required effort were to be expended on peroxides, so attempts at developing a peroxide technique were dropped early in the program. In addition, the time required for Soxhlet extractions, BaP analysis, and subsequent NMR and IR spectra and sample drying created quite a delay in making samples of organic solubles available for CHNSO and paraffin boiling point analyses.

A. Elemental Analysis by Commercial Laboratory

Determination of carbon, hydrogen, nitrogen, and sulfur weight percentages in diesel particulate and organic solubles, and of oxygen weight percentages in organic solubles only was performed by Galbraith Laboratories. Their results were determined by gas analysis following combustion of whole 47mm glass fiber filters (or samples of organic solubles), so the percentages of each compound which constituted final data depended on the total particulate weights supplied to them with the samples. The results were corrected for blank filter content, which was reported to be very low. Galbraith had to split the samples of organic solubles themselves, and sometimes there was not a sufficient amount for oxygen analysis. They were usually sent 3 filters for each particulate sample; one for CHN analysis one for S analysis, and a third to keep should a repeat run be necessary.

B. Analysis for Metals by Commercial Laboratory

Analysis for ten metals (listed in Table 6) was conducted using X-ray fluorescence analysis by Scanning Electron Analysis Laboratories, Inc. They reported their results in $\mu g/cm^2$ on the filter using samples on 47mm Fluoropore filters. This particular filter type was chosen due to its relatively low background metal content and retention properties similar to glass fiber filters (these Fluoropores had 0.5 μm mean flow pore size). Knowing the effective filtration area of the filters and the total particulate weight, the data from S. E. A. L. were adequate for computation of μg metal per filter and fraction of total particulate appearing as each metal. Filter background levels and minimum detection limits were determined separately for each batch of filters analyzed. The portion of each filter analyzed was its center, so concentrations of some materials reported may be somewhat high due to particle dynamic effects.

To illustrate the precision of analysis for metals, Table A-1 of Appendix A lists the minimum detectable limit for each element in each batch of filters submitted. These limits were calculated by the formula

M. D. L. (element "Z") = 3 background counts under peak/peak area counts

x actual concentration of "Z" .

where the actual concentration is obtained from a standard (known) sample. Variation in M. D. L. occurred due to detector aging, instrument anomalies, and so forth. A typical graphical representation of the analyzer output for a sample standard (10μg each Mn, Ni, Cu, Zn, Pb, Sr) is presented in Figure A-1, and Figure A-2 shows a similar output for a typical particulate sample.

C. Analysis for Phenols and Nitrosamines

The SwRI Department of Chemistry and Chemical Engineering worked under this contract to develop analysis methods for phenols, nitrosamines, and organic peroxides in diesel particulate. The nitrosamine technique is capable of detecting 0.1μg or less of dimethylnitrosamine in a sample collected on an 8 x 10 inch glass fiber filter, and approximately 1μg of any of 9 phenols in a sample collected on a 293mm Fluoropore filter. Interference of phenols present on the filter media has been a continuing problem with that analysis. In brief, the phenol and nitrosamine procedures involve a a series of extractions followed by gas chromatograph analysis, and both procedures are given in full on Appendix pages A-5 through A-7. A calibration of the nitrosamine system is shown in Figure A-3, and a typical sample output is shown in Figure A-4. An early calibration of the phenol system is given in Figure A-5, followed by a reagent blank (Fig. A-6), an unused glass fiber filter (Fig. A-7), and a particulate sample on a glass fiber filter (Fig. A-8). A later standard run is shown in Figure A-9, and two blank Fluoropore filter runs in Figures A-10 and A-11. A particulate sample on a Fluoropore filter is given in Figure A-12. Fluoropore filters were used for all record runs.

D. NMR and IR Spectra, and Benzo (α) Pyrene Analysis of Organic Solubles

Southwest Foundation for Research and Education (SFRE) was engaged to assist in analysis by extracting organic solubles from particulate samples on 8 x 10 glass fiber filters, running NMR and IR spectra on the solubles, and finally using the method of Sawicki, et al(7), to determine Benzo (α) pyrene content of the solubles. Soxhlet extraction was used on most of the samples, with benzene, hexane, and methylene chloride all being used as solvents with approximately equivalent results. Ultrasonic extraction was used on some samples for comparison, but its accuracy was not considered superior to Soxhlet, so it did not become the standard technique. A report from SFRE on the BaP analysis, its accuracy and its problems is included in Appendix A, pages A-18 through A-36.

To perform the NMR and IR absorptions, a portion of the solubles was re-dissolved in carbon tetrachloride. Analysis by UV absorption was also attempted early in the program, but the results showed an undefinable hydrocarbon "lump" which made it impractical to pursue UV any further. The IR scan covered wavelengths from 2.5×10^{-6}m to 16×10^{-6}m. The NMR spectrum ranged from about 0 to 8 ppm (or 0 to 8 Hz per MHz), with an oscillator frequency of 60 MHz. A typical IR analysis output is given in Appendix A, Figure A-13, and a similar example of an NMR output is given in Figure A-14.

E. Boiling Point Distribution of Paraffins in Organic Solubles

The U. S. Army Fuels and Lubricants Research Laboratory at SwRI agreed to perform analysis required for boiling point distribution of paraffins in the organic soluble portion of diesel exhaust particulate. Saturate fraction isolation on an activated silica gel column was performed according to ASTM D1319-70, and gas chromatograph analysis of boiling point distribution was performed on organic solubles (both whole sample of solubles and isolated paraffins) according to a modified version of ASTM D2887-73. Fuel samples were subjected to the same analysis procedure. A description of the "Procedure for Saturates in Fuels" is included in Appendix A, pp. A-39 through A-44.

The fuel and all samples and part of the particulate (solubles) samples were chromatographed on a Dexsil 300 column,which is one of the allowable columns for ASTM D2887-73. The remainder of the solubles were chromatographed on SE-30 to improve baseline stability and thus enhance the accuracy of the derived boiling point distributions. All the particulate (solubles) samples analyzed were from tests on the Detroit Diesel 6L-71T engine, since the length of time required for several analyses in series (paraffins being last) did not permit data on samples from the NTC-290 to be ready for this report. A calibration of the Dexsil column is shown in Appendix A, Figure A-15. A calibration of the SE-30 column is shown in Figure A-16, a fuel analysis in Figure A-17, an oil analysis in Figure A-18, and a particulate (solubles) analysis in Figure A-19.

V. CONSTRUCTION AND CALIBRATION OF DILUTION TUNNEL AND SAMPLING DEVICES

In constructing a particulate dilution tunnel for use with large diesel engines, several design conflicts became apparent in transferring the technology and hardware formerly used with light-duty gasoline vehicles. The tunnel as specified by EPA was originally designed and sized for vehicles which produce a maximum of perhaps $3m^3$ (106 ft^3) of exhaust gas per minute on the LA-4 cycle. The large diesels used for this project produced much higher exhaust flows, the maxima being some $18m^3/min$ (650 ft^3/min) for the Cummins NTC-290 and about $27m^3/min$ (950 ft^3/min) for the Detroit Diesel 6L-71T. These maximum exhaust flows were far in excess of total tunnel capacity with no dilution at all, so it became necessary to "split" the exhaust flow and admit only a fraction into the tunnel.

The separation of a fraction of the exhaust to enter the tunnel was accomplished by sizing and restricting exhaust outlets from the muffler, as already described in Section III. Using a fraction of the exhaust in the tunnel introduces another complication, however, because that fraction must be measured without "handling" it (such as with an orifice or laminar flow element). The problem can be resolved by calculating exhaust flow into the tunnel subtractively as follows:

flows into tunnel: dilution air (A) and exhaust (B)
flows out of tunnel: sample (C) and (discarded) dilute exhaust (D)
material balance: $A + B = C + D$
therefore: $B = C + D - A$

Flow C is known by calibration of sampling systems, flow D is known by calibration of the tunnel's primary blower, and Flow A can be measured by an orifice or some other device. Thus flow B (exhaust) can be determined subtractively, and the engine's total particulate emission rate can be computed by the relationship

$$\text{total particulate rate} = (\text{sampled particulate rate})\left(\frac{C + D}{C}\right)\left(\frac{\text{engine exhaust rate}}{C + D - A}\right).$$

Another method for determining total particulate rate (which is the desired end result rather than flow of exhaust into the tunnel) is measurement of both raw and dilute concentrations of a "tracer" gas along with quantities of sample and (discarded) dilute exhaust. For the tunnel used in this project, the "tracer" gas used was NO_x, since it is present in substantial concentrations and remains stable over at least the interval necessary for measurements (approximately 5 seconds). The derivation of this technique is as follows:

RNOX = ppm NO_x in raw exhaust = moles $NO_x/10^6$ moles raw exhaust

DNOX = ppm NO_x in dilute exhaust = moles $NO_x/10^6$ moles (raw exh. + dil. air)

material balance: moles NO_x = constant

therefore: moles raw exhaust = (DNOX/RNOX) (moles raw exh. + dil. air)

= (DNOX/RNOX) (C + D)

and C and D are known quantities.

Total particulate emissions from the engine are computed by

$$\text{total part. rate} = (\text{sampled part. rate})\left(\frac{C + D}{C}\right)\left(\frac{RNOX}{DNOX}\right)\left(\frac{\text{engine exh. rate}}{C + D}\right) .$$

The latter technique was used during this project, but the former is theoretically equivalent and would have the advantage of not requiring a dedicated chemiluminescent NO_x analyzer.

The positive displacement blower used to pull dilution air and exhaust through the dilution tunnel system was calibrated using a large laminar flow element and a bank of electric heaters. The result is shown on page B-2 of Appendix B, with supporting data and calculations on pages B-3 and B-4. It was necessary to extrapolate the line back to a blower Δp of 0.87kPa (3.5 inches H_2O). The higher blower speed (36:26 drive ratio) was used to permit higher tunnel velocities and consequent higher sample acquisition rates. Calibration with the 36:26 drive ratio and 0.87kPa (3.5 inches H_2O) blower Δp yielded a tunnel bulk velocity at the sampling station

$$V_{sb} = N\left[\frac{\text{blower revolutions (counts)}}{\text{time, sec}}\right] \times \frac{T_s}{T_B} \times \frac{p_B}{p_s}$$

where: N = 11.9 for the 4-probe system using 47mm filters
N = 12.4 for the hi-vol system
subscript b indicated "bulk"
subscript s indicated sampling station
subscript B indicates blower inlet.

In order to withdraw an isokinetic sample, however, the tunnel centerline velocity must be used rather than the bulk velocity. The tunnel's velocity profile at the sampling station provides the information required to calculate the centerline velocity from the bulk velocity, in addition to providing data on velocity variation in the sampling zone. Velocity profiles (horizontal and vertical) at the sampling station were acquired with a Thermo Systems hot-film anemometer. The results were less precise than anticipated, due primarily to the influence of large-scale turbulence in the tunnel. Averages over a number of runs gave usable values, however, and the plots shown on page B-5 were constructed from these data. Data and calculations as well as the velocities in the profiles are referred to the duct centerline, and although the "flat" sections of the profiles are not quite normal to the tunnel axis, the deviation from the centerline velocity ($V_{\mathrm{c}\llap{-}}$) is only about ±2% in the sampling zone. The reason for the higher velocities in the upper right section of the tunnel is probably the overhead lighting which strikes the tunnel from that direction. The ±2% velocity gradient in the sampling zone is probably much less a cause of anisokinetic sampling than the large scale turbulence mentioned earlier. Temperature and gas concentration profiles were also taken (vertical only), and the results are shown on pages B-9 and B-10.

Measurement of flow through the hi-vol sampling system using 8 inch by 10 inch glass fiber filters was performed using an orifice mounted about 0.79m (31 in.) downstream of the sampling blower outlet in a 76mm (3 in) O.D. "tailpipe". The orifice equation was determined by the ASME flowmeter handbook(8) procedure as

$$\text{mass flow} = 4.65\,(\Delta p\rho)^{0.5}\ \text{lbm/min} = 2.11\,(\Delta p\rho)^{0.5}\ \text{kg/min},$$

where Δp is in inches of H_2O and ρ is in lb_m/ft^3. Flow through the hi-vol unit was set according to the relationship

$$\Delta p_{or}\ (\text{isokinetic sample}) = \frac{\rho_s^2\, V_{sb}^{\ 2}}{4064\rho_{or}}\ ,$$

where the subscript "or" denotes the orifice station downstream of the hi-vol blower.

Flow through the 4-probe system was set by calibrated rotameters and measured (totalized) by calibrated dry gas meters. Using the calibrations, flow through this system was set according to the relationship

$$\dot{m} = (x)\ V_{sb}\quad ,$$

where x was 0.00151 for two of the systems, and 0.00152 for the others. (The probe inlet area of both the hi-vol system and the 4-probe system had to be reduced from their original sizes (as specified for testing of gasoline engines) to prevent inordinately high filter face velocities and pressure drops. Even with these area reductions (and their consequent flow reductions), filters often plugged before the desired sampling time had elapsed. Calibration curves and calculations on these two sampling systems (hi-vol and 4-probe) are given on pages B-11 through B-13.

When the filter samples for phenol analysis were taken, Fluoropore filters had to be used to minimize background problems. These filters (293 mm diameter) had a much higher pressure drop per unit volume flowrate than glass fiber filters, so the standard hi-vol blower could no longer be used.

In its place, another system was constructed using an orifice and a small Roots pump to measure and withdraw sample. This system used the same orifice equation as the hi-vol system, but the operating point had to be changed as the filter plugged because the orifice was under an increasing vacuum as the run progressed. To maintain the isokineticity of the sampling as long as possible, the curve shown on page B-14 of Appendix B was used by the sampler operator to regulate a bypass (inlet) downstream of the orifice. Since the Fluoropore filter did plug rather rapidly, sampling was usually conducted until the sample rate fell to about 0.6 times the isokinetic rate. Simplified operating guides for the tunnel and samples are given on page B-15.

The orifice used to measure engine air flow was calibrated against a laminar flow element having calibration traceable to NBS standards. The final air flow equation (derived by application of the least squares method to logs of Δp and mass flow) is

$$\dot{M}_a = 40.64\ (\Delta p \rho)^{0.4842}\ \text{kg/min} = 89.60\ (\Delta p \rho)^{0.4842}\ \text{lb}_m/\text{min},$$

and the applicable calibration data and curve are given on pages B-29 and B-30. Exhaust mass flow is air flow plus fuel flow (which was measured by a flow bridge-type instrument).

The final particulate sampling system to be discussed was called the "ERC sampler," and it was built by the Environmental Research Corporation for EPA under an earlier contract. This sampler was independent of the dilution tunnel, and withdrew its sample from the engine's exhaust pipe upstream of the muffler. After the unit was made operable by a number of minor modifications and repairs, it was decided that the instructions supplied with it were indecipherable. The sampler's principles of operation were reviewed, and a more usable set of instructions was devised with considerable effort. These instructions appear as pages B-16 through B-23 of Appendix B, and the calculations and considerations leading to the instructions are given as pages B-24 through B-28.

The ERC sampler drew both exhaust and dilution air into a central chamber, using a vacuum blower as the gas-handling device. Exhaust was drawn through a heated sample line containing a venturi for flow measurement. This exhaust was allowed to impinge upon a (theoretically) equal flow of air in the center of the dilution chamber, and additional dilution air was added through the wall of the chamber (it was made of fine mesh). Provision was made for sampling from the total dilute flow at either 1 CFM (0.028 m^3/min) or 5 CFM (0.142 m^3/min), using a separate filter holder, sample pump, flowmeter, and dry gas meter. The 1 CFM flowrate was used for this project, and the remainder of the (nominal) 50 CFM (1.42 m^3/min) dilute exhaust flow was discarded.

VI. PLANS FOR ACQUISITION AND REDUCTION OF DATA

Since the total number of samples taken in the methodology demonstration portion of this project was extremely large, a test plan was devised to meet project objectives while avoiding unnecessary duplication. This plan provided ample information on which types of analysis are most useful for fuel and additive qualification. The minimum plan is summarized in Table 7, and it was followed more closely for the Cummins NTC-290 engine than for the Detroit Diesel-Allison 6L-71T engine (the test plan was still being finalized while the 6L-71T engine was under test). A number of duplicate and supplementary runs was made on each engine as required to fully document the test results. The actual number of independent analytical determinations made on each engine is summarized in Table 8 along with the number which would have resulted had the test plan followed strictly.

Procedures for data reduction were really the final technical developments necessary to calculate engine total particulate output from data obtained during the course of a test, based on calibrations and computations already presented. Data acquired during a test are perhaps best illustrated by the data forms actually filled out during a test, so examples of the three types of forms are given as pages C-2 through C-4 of Appendix C. For a given test only half of each data form would be completed (top or bottom).

Mathematical development of data reduction procedures is given as pages C-5 and C-6, based largely on the results of calibrations and calculations discussed in Section V. Although the calculations are compact enough to be performed by hand for a few cases, the large number of samples taken for this project made computer processing more economical in the long term. Examples of the encoding sheets from which data were keypunched (12 data cards per test) are given as pages C-7 and C-8. The computer program used for processing is included as pages C-9 through C-12, and sample results are given on pages C-13 and C-14.

Developing procedures for steady-state runs (all those other than the composites) was relatively simple, since most of the major data items remained rather stable. Obtaining a sample on one filter which was a true composite for the 13-mode test, however, required that the total amount of raw exhaust gas filtered in each mode be proportional to the product of engine exhaust mass flowrate and the time-based weighting factor for that mode. In mathematical terms

$$m_i = C_1 \left(\frac{E+D}{E}\right)_i W_i (\dot{M}_e)_i \text{ or } (M_{or})_i = C_2 \left(\frac{E+D}{E}\right)_i W_i (\dot{M}_e)_i \ ,$$

TABLE 7. MINIMUM TEST PLAN AND DATA MATRIX FOR EACH ENGINE AND EACH FUEL

Operating condition		Analysis codes[a] by sampling system			
		Four 47mm filters		Hi-vol system	
Speed	Load, %	First run	Repeat	First run	Repeat
Idle	0	1, 2, 5, 8		1, 3, 4, 6	1, 7
Peak torque	0	1, 2, 5, 8		1, 3, 4, 6	
Peak torque	25	1, 2[b], 5		1	
Peak torque	50	1, 2, 5, 8		1, 3, 4, 6	
Peak torque	75	1, 2[b], 5		1	
Peak torque	100	1, 2, 5, 8		1, 3	1, 7
Rated	0	1, 2, 5, 8		1, 3	
Rated	25	1, 2[b], 5		1	
Rated	50	1, 2, 5, 8		1, 3	
Rated	75	1, 2[b], 5		1	
Rated	100	1, 2, 5, 8		1, 3, 4, 6	1, 7
Composite		1, 2, 5	1, 5	1, 3, 4, 6	1, 7

[a] Analysis codes

1. gravimetric
2. metals
3. organic solubles, BaP, IR, NMR
4. paraffins in organic solubles
5. SCHN in particulate
6. SCHNO in organic solubles
7. phenols and nitrosamines
8. ERC gravimetric

[b] Fuel "B" only

TABLE 8. PLANNED AND ACTUAL NUMBERS OF ANALYSES CARRIED OUT ON EACH ENGINE

Type of analysis	Number of analyses by engine		
	Planned (both)	D.D. 6L-71T	Cum. NTC-290
gravimetric	408	592	524
metals	54	54	58
SCHN (particulate)	78	65	72
organic solubles, (BaP, IR, NMR	48	41	54
paraffin boiling range (solubles)	30	21	---[a]
SCHNO (solubles)	30	13	8[b]
phenols, nitrosamines	24	20	21

[a] Insufficient time to complete these analyses

[b] Insufficient sample to perform the planned number of tests

where: i = individual mode, i = 1, 2, 3, ..., 13;

$m_i = (\dot{m}_i)\ (\text{time})_i$ = total dilute exhaust filtered in mode i, 4 x 47 system, lb_m;

$(M_{or})_i = (\dot{M}_{or})_i\ (\text{time})_i$ = total dilute exhaust filtered in mode i, hi-vol system, lb_m;

$(\text{time})_i$, = time in mode i, sec;

$(\dot{M}_e)_i$ = engine exhaust flowrate in mode i, lb_m/min;

W_i = time-based weighting factor;

E_i = exhaust flow through tunnel, lb_m/min; and

D_i = diluent flow through tunnel, lb_m/min.

Note that

$$(\text{time})_i = \frac{C_1}{\dot{m}_i}\left(\frac{E+D}{E}\right)_i W_i(\dot{M}_e)i = \frac{C_2}{(\dot{M}_{or})_i}\left(\frac{E+D}{E}\right)_i W_i(\dot{M}_e)_i \ ,$$

so

$$C_1 = C_2 \frac{\dot{m}_i}{(\dot{M}_{or})_i}$$

Therefore, since both $\dot{m}_i$ and $(\dot{M}_{or})_i$ are essentially fixed by isokinetic considerations, it is sufficient to use only one of the $(\text{time})_i$ equations above for computation purposes. The quantities $\left(\frac{E+D}{E}\right)_i$, W_i, $(\dot{M}_e)_i$, and $(\dot{M}_{or})_i$ are known or can be calculated from experimental data. If a value for any $(\text{time})_i$ is assumed, the constant C_2 can be calculated and then the other $(\text{time})_i$ can also be calculated. To determine whether or not our choice of C_2 is reasonable, we can compute

$$(\text{time}) = \sum (\text{time})_i \ ,$$

and choose a higher or lower value of C_2 to make (time) more reasonable.

To minimize the complexity of the 13-mode test, it was decided to determine the $(E+D/E)_i$ with both the dump valves in a constant position such that maximum exhaust back pressure existed only for the rated speed, 100 percent load condition. This decision means that we did not have the absolute maximum particulate collection per unit time, but experimental data showed that an adequate amount should be collected in a test of about 40 minutes' duration. It was also possible, of course, to determine $(M_e)_i$ and a good average value for M_{or} while measuring the dilution ratios. Data and some calculations are given in Table 9 and on the lines just below Table 9 for the Detroit Diesel 6L-71T engine. Note that the technique

TABLE 9. DATA AND CALCULATIONS USED TO DETERMINE MODE TIMES FOR THE DETROIT DIESEL 6L-71T ENGINE

i = Mode	W_i	$\left(\frac{E+D}{E}\right)_i$	$(\dot{M}_e)_i$	Time in mode (min) by assumption	
				1	2
1	0.20 ÷ 3	32.2	9.85	2.00	1.08
2	0.08	22.6	35.78	6.12	3.31
3	0.08	19.8	37.63	5.64	3.05
4	0.08	20.4	41.64	6.43	3.48
5	0.08	19.4	46.73	6.86	3.71
6	0.08	18.1	54.14	7.42	4.01
7	0.20 ÷ 3	31.5	9.85	1.96	1.06
8	0.08	12.9	74.43	7.27	3.93
9	0.08	14.4	67.45	7.35	3.97
10	0.08	15.8	60.36	7.22	3.90
11	0.08	16.3	54.16	6.68	3.61
12	0.08	17.6	50.79	6.76	3.66
13	0.20 ÷ 3	27.1	9.85	1.68	0.91
TOTAL = (time) =				73.39	39.68

ASSUMPTION 1: $(\text{time})_1 = 2.00$ min ∴ $C_2 = 0.1665$
conclusion: (time) too long ∴ assume smaller C_2

ASSUMPTION 2: $C_2 = 0.09$
conclusion: (time) is OK, but combine 1, 7, and 13 to make one (longer) idle mode so technicians will have adequate time to gather data

converges rapidly on the desired value of (time). Similar information for the Cummins NTC-290 engine is shown in Table 10, although the schedule there has already been reduced to 11 modes as suggested following Table 9. The final mode times in seconds and cumulative seconds are shown for both engines in Table 11. Although the constants are different for any two engines and dilution tunnels, a similar approach to mode weighting by controlling sampling times should be valid for any system. This schedule yields the desired result, that is, weighting of modes so that a single filter is representative of a 13-mode test as that test is defined. Runs were sometimes repeated with the same filter in place when too small an amount of particulate was collected.

TABLE 10. DATA AND CALCULATIONS USED TO DETERMINE MODE TIMES FOR THE CUMMINS NTC-290 ENGINE

i = Mode	W_i	$\left(\frac{E+D}{E}\right)_i^a$	$(\dot{M}_e)_i$	Time in mode (min) by assumption 1	Time in mode (min) by assumption 2
1	0.08	22.2	23.12	1.41	3.18
2	0.08	22.5	24.56	1.52	3.43
3	0.08	21.9	26.59	1.60	3.61
4	0.08	20.0	29.38	1.62	3.64
5	0.08	19.9	33.02	1.81	4.07
6	0.20	25.3	9.53	1.66	3.74
7	0.08	12.9	48.63	1.73	3.89
8	0.08	14.1	43.07	1.67	3.77
9	0.08	15.4	38.42	1.63	3.67
10	0.08	16.7	34.97	1.61	3.62
11	0.08	16.7	31.75	1.46	3.29
			TOTAL = (time) =	17.73	39.91

[a] Valve positions: large--open; small--5.5 turns closed

ASSUMPTION 1: $C_2 = 0.06 \therefore (\text{time})_i = 0.0344\ W_i(\dot{M}_e)_i \left(\frac{E+D}{E}\right)_i$

conclusion: (time) too short $\therefore$ assume smaller C_2

ASSUMPTION 2: $C_2 = 0.135 \therefore (\text{time})_i = 0.0775\ W_i(\dot{M}_e)_i \left(\frac{E+D}{E}\right)_i$

conclusion: (time) is OK

TABLE 11. WEIGHTING SCHEDULE FOR 11-MODE "COMPOSITE" RUNS

i = Mode	Condition		D. D. 6L-71T		Cum. NTC-290	
	rpm	Load, %	Mode time, sec.	Cumul. time, sec.	Mode time, sec.	Cumul. time, sec.
1	peak torque	0	198	198	191	191
2	peak torque	25	183	381	206	397
3	peak torque	50	208	589	217	614
4	peak torque	75	222	811	219	833
5	peak torque	100	240	1051	244	1077
6	Idle	0	182	1233	224	1301
7	rated	100	235	1468	233	1534
8	rated	75	238	1706	226	1760
9	rated	50	234	1940	220	1980
10	rated	25	216	2156	217	2197
11	rated	0	219	2375	197	2394

VII. RESULTS OF METHODOLOGY DEMONSTRATION

The project being reported on here was a very ambitious one, including development or perfection of several particulate sampling techniques, acquisition of gaseous emissions and smoke data as a function of fuel composition, and development and demonstration of a number of techniques for analyzing particulate content. Accordingly, since no data base was available which applied to many of the constituents of interest, most of results presented here cannot be considered entirely authoritative until they can be tested against further research. Time and cost limitations also served to restrict the number and range of particulate analyses conducted, resulting in a less-than-complete picture of fuel, additive, and engine effects on emission of a number of constituents in particulate form. The demonstration did, however, provide useful information regarding several classes of compounds and elements. It also gave strong indications of the priorities which should be attached to further research on many constituents by finding them to be present in either significant or insignificant (or unmeasureable to the limits of present techniques) quantities.

Due to the variety of analyses conducted, this section will be subdivided by type of analysis for clarity. These subdivisions are ordered as follows:

- Federal smoke (opacity) evaluations
- steady-state smoke measurement by Bosch spotmeter and PHS opacity meter
- gravimetric (emission mass rate and concentration) analysis
- constituents of particulate
  - sulfur, carbon, hydrogen, and nitrogen by combustion total organic solubles by soxhlet extraction
  - metals by X-ray fluorescence
  - phenols and nitrosamines by extraction and chromatography
- analyses of the organic soluble fraction of particulate
  - sulfur, carbon, hydrogen, nitrogen, and oxygen by combustion
  - paraffin boiling point distribution
  - BaP (benz-α-pyrene)
  - NMR and IR spectra

Care must be taken to note the qualifications attached to all the results, especially those for which no comparative data are available in the literature.

It should be noted here that some of the particulate data acquired for the Detroit Diesel 6L-71T engine are probably representative of an engine with one or more malfunctioning injectors, limiting the usefulness of these

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data for fuel-to-fuel and engine-to-engine comparisons. As the data are presented, those suspect from this standpoint will be identified and qualified. No such problem occurred during operation of the Cummins NTC-290 engine.

A. Federal Smoke (Opacity) Evaluations

One intent of these measurements was to document the extent to which the two engines tested appeared to be typical of their respective makes and models as compared to Federal certification data. They also served as a comparison between fuels and could perhaps be used in a correlation format as a rough predictor of total particulate emission rate (although the establishment of such a correlation is beyond the scope of this project). It should be noted that the "Certification data" do not agree in all cases with smoke from the test engines but that disagreement such as that present can exist from engine to engine of a given type. Further, the "B" factor data for the Cummins NTC-290 appear to be quite a bit higher than "Certification" results, but data from various issues of the Federal Register strongly support a value of 4.0 to 5.0 percent rather than the 1.7 percent figure supplied by Cummins personnel.

Both the Federal Smoke Tests and the steady-state tests (described in the next section) are measures of the density or "opacity" of the smoke plume generated by diesel engines. The measurement device employed for these tests was the PHS smokemeter, consisting of a light source and a detector on opposite sides of the plume (plus associated control and read-out equipment). Most of the smoke measurements taken on the two test engines were quite low given the operating conditions, especially the steady-state values. Smoke opacity of about 2 percent is considered near the visibility limit, while 20 percent opacity is considered quite heavy. Federal regulations on smoke applicable to the test engines are an "A" factor of 40 percent and a "B" factor of 20 percent. The regulation including the "C" factor (50 percent maximum) did not go into effect until the 1974 model year.

Federal smoke data on both engines are summarized in Table 12, indicating mixed and rather minor variations among the fuels not containing additives. The additive in fuel "A+" seemed to have little effect on smoke from the Detroit Diesel engine, but a measureable suppressant effect for the Cummins engine. The organo-metallic additive in fuels "B+" and "C+", however, had a distinct effect on visible smoke from both engines in this transient procedure (achieving nominal 50% reductions). These reductions are considered highly significant. Later in this section the degree to which this trend does or does not hold for particulate mass emissions will be examined. Complete data on Federal smoke tests are presented on pages D-2 and D-3 of Appendix B.

TABLE 12. AVERAGE FEDERAL SMOKE TEST RESULTS, TWO ENGINES AND SIX FUELS, COMPARED TO FEDERAL CERTIFICATION RESULTS

Engine	Result	Certification data	Average PHS smokemeter % opacity by fuel					
			A	B	C	A+[a]	B+[b,c]	C+[b,c]
D.D. 6L-71T	"A" factor	12.8[d]	14.3	12.3	15.3	15.5	3.2	8.0
	"B" factor	2.4[d]	3.6	1.9	2.3	3.5	1.0	1.4
	"C" factor	27.0[d]	20.4	19.1	22.2	22.5	5.2	11.8
Cum. NTC-290	"A" factor	11.2[e]	7.0	7.8	7.9	4.8	2.5	3.8
	"B" factor	1.7[e]	4.3	4.2	4.4	3.6	1.4	1.6
	"C" factor	14.8[e]	10.8	11.1	10.3	7.0	4.1	6.1

[a] contains ignition accelerator additive

[b] contains smoke suppressant additive

[c] injector repair prior to running this fuel for 6L-71T engine

[d] average of 1973 and 1974 data

[e] data from factory, reportedly a composite from several similar engines

B. Steady-State Smoke Tests (PHS opacity and Bosch spot)

These tests were conducted to document via accepted methods the appearance or density of the exhaust plumes on which particulate mass and concentration data were acquired. The operating conditions for these tests were the same steady-state modes used in the particulate evaluations, and Tables 13 and 14 present the results as averages for the two engines. It is apparent that for steady-state conditions, both engines have low smoke levels for all fuels and operating points. Both engines employ turbochargers, meaning that all steady-state operation occurs with comparatively lean mixtures (as compared to some naturally-aspirated engines).

Even though smoke levels were low, limiting results to one or two significant figures, there were mixed trends toward higher opacity and higher Bosch numbers as power output increased at a given speed. It is assumed that these trends were somewhat dependent on turbocharger performance and the resulting fuel/air ratios, although a direct correlation is not apparent. Reductions in smoke opacity and Bosch numbers due to use of the smoke-suppressant additive (Lubrizol 8005 in B+ and C+) were not so dramatic as for Federal smoke tests, but they still ran around 50 percent for conditions other than idle and zero load. These reductions are considered quite significant.

TABLE 13. SUMMARY OF STEADY-STATE SMOKE DATA FOR DETROIT DIESEL 6L-71T ENGINE

Mode	Engine rpm and load	PHS smokemeter % opacity by fuel code					
		A	B	C	A + add.	B + add.[a]	C + add.[a]
1	Idle	0.3	0.3	0.3	0.4	0.2	0.3
2	1600 - 0%	0.7	0.4	0.3	0.6	0.6	0.4
3	1600 - 25%	0.8	0.6	0.5	0.8	0.6	0.6
4	1600 - 50%	1.0	0.8	0.8	1.0	0.6	0.7
5	1600 - 75%	1.7	1.1	1.1	1.6	1.2	0.8
6	1600 - 100%	3.4	1.6	1.9	3.3	2.6	1.3
7	Idle	0.2	0.2	0.2	0.2	0.2	0.3
8	2100 - 100%	1.9	1.0	1.1	1.6	1.6	1.0
9	2100 - 75%	1.4	0.8	0.9	1.0	1.2	0.9
10	2100 - 50%	1.2	0.7	0.9	1.0	0.9	0.7
11	2100 - 25%	1.0	0.8	0.8	0.9	0.9	0.8
12	2100 - 0%	1.1	0.9	0.9	1.2	1.4	0.8
13	Idle	0.2	0.3	0.2	0.2	0.2	0.3

Mode	Engine rpm and load	Bosch smoke number by fuel					
		A	B	C	A + add.	B + add.[a]	C + add.[a]
1	Idle	0.1	0.1	0.1	0.1	0.2	0.1
2	1600 - 0%	0.2	0.1	0.1	0.2	0.3	0.1
3	1600 - 25%	0.5	0.2	0.2	0.4	0.3	0.1
4	1600 - 50%	0.7	0.4	0.4	0.6	0.7	0.2
5	1600 - 75%	1.1	0.6	0.6	1.1	0.7	0.3
6	1600 - 100%	1.9	1.0	1.1	1.8	1.2	0.6
7	Idle	0.1	0.2	0.1	0.1	0.2	0.1
8	2100 - 100%	0.9	0.3	0.3	0.8	0.4	0.2
9	2100 - 75%	0.7	0.3	0.2	0.4	0.4	0.2
10	2100 - 50%	0.5	0.3	0.2	0.4	0.4	0.1
11	2100 - 25%	0.5	0.2	0.2	0.3	0.4	0.1
12	2100 - 0%	0.7	0.4	0.4	0.7	0.6	0.3
13	Idle	0.1	0.2	0.1	0.1	0.2	0.1

[a] some of these results reflect minor injector problems - use care in comparing them to those from other fuels

TABLE 14. SUMMARY OF STEADY-STATE SMOKE DATA FOR CUMMINS NTC-290 ENGINE

Mode	Engine rpm and load	PHS smokemeter % opacity by fuel code					
		A	B	C	A + add.	B + add.	C + add.
1	Idle	0.6	0.8	1.0	0.8	0.8	0.6
2	1500 - 0%	0.7	1.1	1.0	0.5	0.6	1.0
3	1500 - 25%	1.5	1.8	2.0	1.0	0.8	1.0
4	1500 - 50%	1.6	2.5	2.2	1.4	0.6	1.0
5	1500 - 75%	1.4	2.1	1.7	0.8	0.5	1.0
6	1500 - 100%	1.9	2.1	2.0	1.1	0.7	1.1
7	Idle	0.3	0.5	0.4	0.3	0.2	0.7
8	2100 - 100%	2.6	3.3	2.8	2.2	0.8	1.3
9	2100 - 75%	1.8	2.1	2.2	1.6	0.4	1.0
10	2100 - 50%	2.0	2.5	2.7	1.8	0.6	1.0
11	2100 - 25%	2.4	2.2	2.8	2.0	0.8	1.2
12	2100 - 0%	1.2	1.1	1.8	1.0	0.8	1.3
13	Idle	0.4	0.6	0.4	0.4	0.4	0.8

Mode	Engine rpm and load	Bosch smoke number by fuel					
		A	B[a]	C	A + add.	B + add.	C + add.
1	Idle	0.1	0.2	0.2	0.2	0.2	0.2
2	1500 - 0%	0.4	0.6	0.6	0.4	0.5	0.4
3	1500 - 25%	0.9	1.1	1.1	0.9	0.6	0.4
4	1500 - 50%	1.1	1.4	1.2	1.0	0.6	0.4
5	1500 - 75%	0.9	1.1	1.0	0.9	0.4	0.2
6	1500 - 100%	1.2	1.2	1.1	1.1	0.6	0.4
7	Idle	0.2	0.2	0.2	0.2	0.2	0.2
8	2100 - 100%	1.6	1.8	1.7	1.6	0.6	0.6
9	2100 - 75%	1.2	1.4	1.2	1.2	0.4	0.3
10	2100 - 50%	1.3	1.4	1.5	1.4	0.5	0.4
11	2100 - 25%	1.4	1.5	1.5	1.5	0.6	0.6
12	2100 - 0%	0.7	0.8	0.9	0.8	0.6	0.4
13	Idle	0.2	0.1	0.2	0.2	0.2	0.2

[a] check after particulate work on fuel "B" gave 0.2 at idle, 1.2 at 1500 rpm and 100% load, and 1.8 at 2100 rpm and 100% load

It is interesting to note that different mixed trends toward higher values were also the case for particulate mass emissions and particulate concentrations. It is possible, therefore, that while smoke opacity is due to some sort of exhaust particulate, this light-blocking material is not the major factor in particulate mass. This situation is obviously the case for tests involving use of the organo-metallic smoke suppressant additive, since opacity decreased significantly and particulate mass generally increased as compared to tests conducted without the additive.

C. 13-Mode Gaseous Emissions Tests

Gaseous emissions from the two engines were measured on all six test fuels using the well-accepted 13-mode procedure for diesels. These data are intended to document any variation in emissions caused by fuel composition, and the average results are given in Table 15.

TABLE 15. AVERAGE 13-MODE GASEOUS EMISSIONS RESULTS

Engine	Fuel code	Number of runs	Cycle composite emissions, g/hp hr			
			HC[a]	CO	NO_x	HC[a] + NO_x
Statutory limits (1974)			----	40.	----	16.
Detroit Diesel 6L-71T	A	2	0.96	2.20	11.8	12.8
	B	6	0.68	2.46	12.5	13.2
	C	3	1.00	2.33	11.4	12.4
	A+	2	1.12	2.22	10.4	11.5
	B+	2	1.18	3.14	11.2	12.4
	C+	2	1.32	3.02	11.5	12.8
Cummins NTC-290	A	2	0.30	2.50	12.0	12.3
	B	8	0.33	2.46	12.5	12.8
	C	2	0.28	2.38	12.4	12.7
	A+	2	0.26	2.46	12.1	12.4
	B+	2	0.40	2.79	12.5	12.9
	C+	3	0.36	2.93	12.6	13.0

[a] some data for 6L-71T engine may be representative of slight malfunctions in injection system

The data in Table 15 show that fuel variation had little influence on regulated emissions. There is perhaps a weak indication that HC and CO emissions from these engines increased slightly when fuels containing the organo-metallic additive were used (B+ and C+), but a great deal more testing would be necessary to substantiate it. Gaseous emissions data are given by individual runs on pages D-4 and D-5 of Appendix D.

D. Gravimetric Analysis - Particulate Mass Emissions and Concentrations

The data in this subsection are the cornerstone of all the chemical and physical analyses performed on particulate samples from the engines tested. Computation of particulate mass rates and concentrations has already been discussed, but it is important to recall that all rates and concentrations of particulate constituents are calculated by assuming that they are known fractions of the total collected sample. For these reasons the multiplicity of data presented here is not superfluous, but rather only necessary documentation.

Basic processing of data by computer yielded particulate data in grams per hour and in micrograms per standard cubic meter of exhaust gas. The mass rates turned out to be in a useable range numerically (mostly between 1 and 100g/hr), but the concentrations were unwieldy (mostly in the range of 1000 to 100,000). Accordingly, particulate concentration data will be summarized in milligrams per standard cubic meter of exhaust gas for ease of presentation. Summaries of average particulate mass rates (g/hr) and concentrations (mg/m^3) are given by engine, fuel, and operating condition in Appendix E, pages E-2 through E-11.

For presentation in the text, particulate emissions have been calculated on a specific basis. The average data from runs using 47mm filters have been divided by the average fuel rates (different for each fuel), yielding fuel specific data for each mode (and for composites) in grams of particulate per kilogram of fuel consumed. This technique circumvents the problems inherent in presentation of brake specific data by mode where the power output can be zero (or near zero). The fuel specific data are presented in Table 16 for both engines, and they have been graphed in Figures 20 and 21.

In discussing these fuel specific results, it should first be noted that some of the data for the 6L-71T engine are probably representative of an engine with one or more malfunctioning injectors. These problems occurred during testing of fuels B+ and C+, and efforts were made to correct them, but they obviously had some influence on the results. If fuels B+ and C+ are eliminated from the comparison, the 6L-71T engine still emitted considerably more particulate per unit of fuel consumed than the NTC-290. As an average over the composite runs, fuel specific particulate emissions from the 6L-71T engine were about 3.2 times those from the NTC-290 (factors varied from 2.3 to 3.9 by fuel).

Other trends became obvious by examining Figures 20 and 21, beginning with distinct variation patterns related to engine power level and operating speed. Another trend visible in the Cummins NTC-290 data is consistently lower fuel specific particulate for fuels A and A+ than for

TABLE 16. FUEL SPECIFIC PARTICULATE RESULTS FROM TWO ENGINES OPERATED ON SIX FUELS
47mm GLASS FIBER FILTERS

Engine	rpm	Load, %	Grams particulate per kilogram fuel by fuel code					
			A	B	C	A+	B+	C+
6L-71T	idle	---	5.9	15.	6.6	3.0	1.7	6.5
	1600	0	5.0	6.5	5.3	5.1	9.4	12.
	1600	25	2.9	4.0	3.5	3.6	13.	13.
	1600	50	2.6	3.5	3.0	2.8	15.	6.4
	1600	75	2.4	3.7	2.5	2.3	4.7	3.4
	1600	100	1.8	1.9	1.7	1.7	3.8	2.6
	2100	0	5.8	6.3	5.2	4.8	15.	7.7
	2100	25	3.8	3.6	3.1	3.0	24.	6.5
	2100	50	3.9	3.5	3.5	3.4	11.	5.0
	2100	75	2.5	3.1	2.6	2.9	6.1	4.7
	2100	100	2.6	2.9	1.8	2.7	4.1	3.0
	Composite		3.8	3.7	3.4	3.7	7.2	3.7
NTC-290	idle	---	0.49	2.8	1.2	0.35	2.9	2.2
	1500	0	1.2	2.1	1.7	1.4	3.4	2.6
	1500	25	1.1	1.9	1.4	1.2	2.3	2.1
	1500	50	0.87	1.7	1.3	0.95	2.1	1.8
	1500	75	0.81	1.2	0.78	0.73	1.8	1.6
	1500	100	0.54	0.98	0.62	0.54	1.7	1.3
	2100	0	1.6	2.6	2.3	1.9	3.4	2.8
	2100	25	2.0	3.3	2.4	1.9	3.9	3.0
	2100	50	1.4	2.1	1.6	1.1	2.2	1.8
	2100	75	1.0	1.7	1.0	0.96	1.9	1.6
	2100	100	0.93	1.3	1.0	1.1	1.8	1.5
	Composite		1.0	1.6	1.2	0.95	2.0	1.3

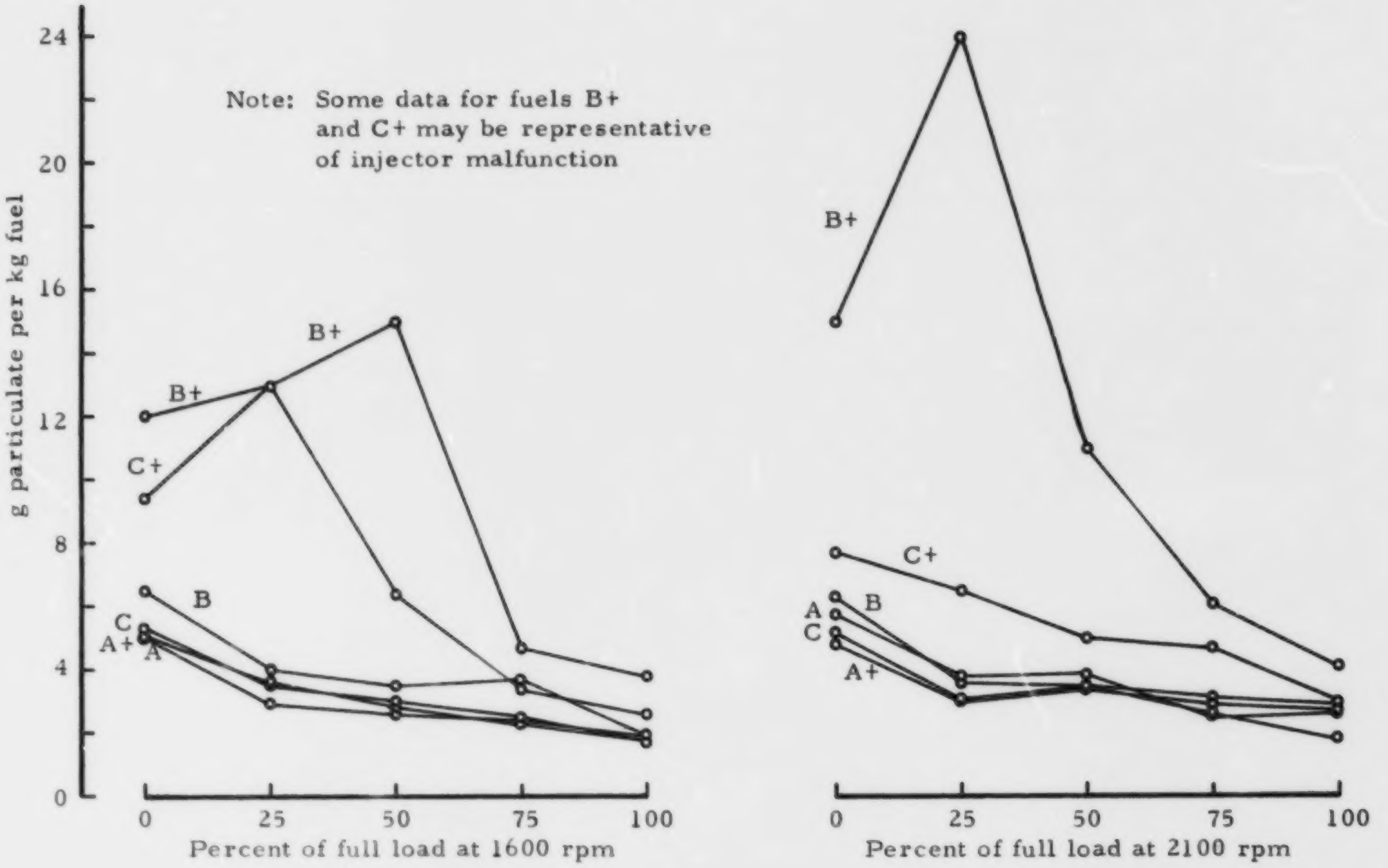


FIGURE 20. FUEL SPECIFIC PARTICULATE EMISSIONS FROM A DETROIT DIESEL-ALLISON 6L-71T ENGINE, FUEL AS PARAMETER

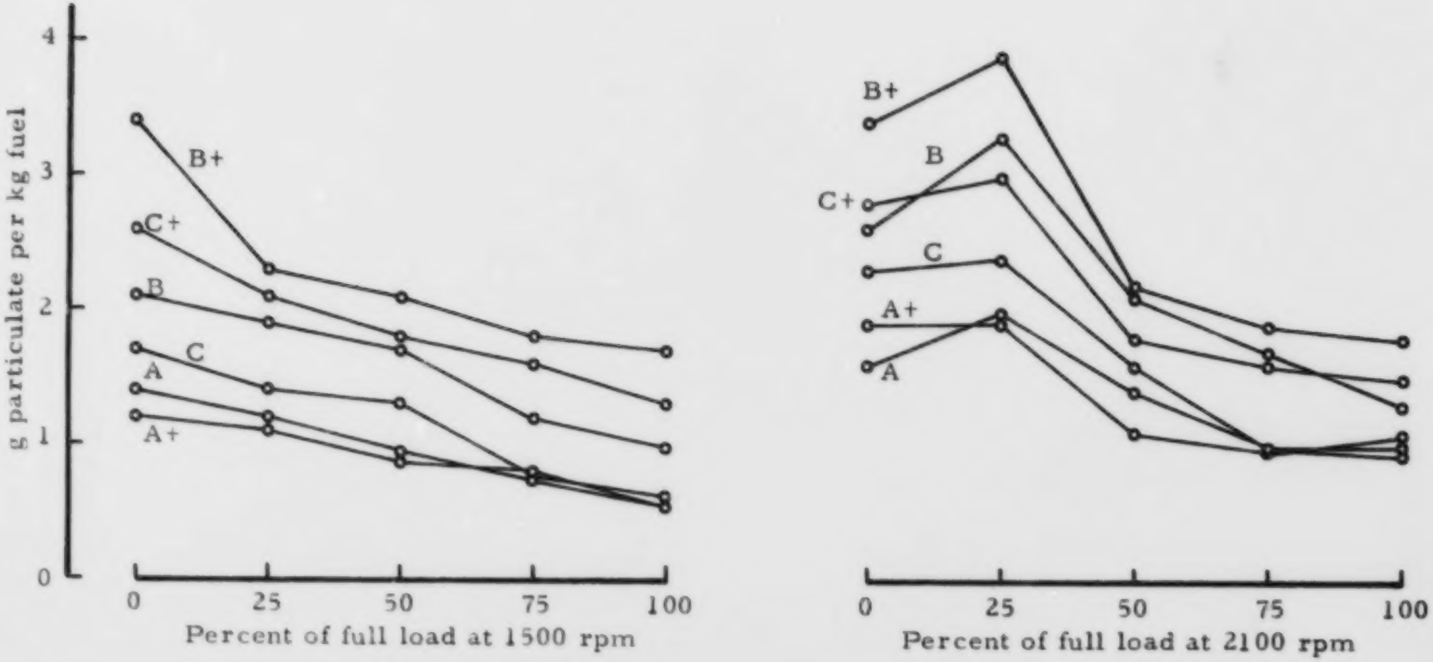


FIGURE 21. FUEL SPECIFIC PARTICULATE EMISSIONS FROM A CUMMINS NTC-290 ENGINE, FUEL AS PARAMETER

the others. Fuel A was the lightest fuel tested, while C and B were progressively heavier. Fuel specific particulate was consistently higher for fuel B+ than for fuel B and consistently higher for fuel C+ than for fuel C. These results indicate that particulate emissions were greater when the organo-metallic smoke-suppressant additive was used for the engines and fuels tested in this study.

Although it is not practical to attempt mode-by-mode brake specific particulate computation, as mentioned earlier, it is relatively straightforward to compute brake specific values for composite runs. The results of such computations are shown in Table 17, confirming the previously-mentioned difference between the two engines tested.

TABLE 17. COMPOSITE BRAKE SPECIFIC PARTICULATE EMISSIONS FROM TWO ENGINES OPERATED ON SIX FUELS, 47mm GLASS FIBER FILTERS

	grams particulate per kW hr by fuel code					
Engine	A	B	C	A+	B+	C+
6L-71T	0.90	0.94	0.87	0.94	2.0[a]	1.0[a]
NTC-290	0.27	0.46	0.34	0.27	0.58	0.38

[a] these data may be representative of an engine with one or more malfunctioning injectors

Although the sampling and calculation methods were quite different, the data in Table 17 agree reasonably well with earlier work on diesel particulate(9) which showed a range of 0.28 to 3.0 g/kW hr for eight engines operating on a fuel similar to fuel B.

For this presentation of specific particulate data, values obtained using 47mm glass fiber filters have been used. The reasons for this choice are primarily the sheer weight of data available and the good consistency observed in the data. Values from tests using the hi-vol system averaged somewhat higher than those from tests using the 47mm system, probably due to the smaller surface-to-volume ratio of the hi-vol system. Hi-vol data were not quite as comprehensive as 47mm glass fiber data, however, thus the latter was chosen. Data generated using 47mm Fluoropore filters could have been used, but three glass fiber filters were acquired for each Fluoropore, providing a better data base.

Only a few runs were made with 293mm Fluoropore filters, so they were not considered for further analysis. A number of runs were made with the ERC sampler-diluter, but it was incapable of sampling during composites. In addition, the repeatability of ERC data was generally poor, and nominal values deviated widely from those obtained via dilution tunnel measurements. For mass particulate rates averaged over four fuels (6L-71T) or six fuels (NTC-290) at single operating conditions, coefficients of variation for ERC samples were consistently higher than tunnel-collected samples (coefficient of variation is standard deviation divided by mean = $s/\overline{x}$). For the NTC-290, the average coefficient of variation for ERC samples was 0.46, while that for similar filters (47mm Fluoropore) collected via tunnel was 0.39. For the 6L-71T, the average coefficient of variation for ERC samples was 0.47 and that for tunnel-collected samples was 0.25.

During most sampling conditions with the NTC-290 engine, ERC particulate mass rate results were from 40 percent to 60 percent of those obtained by tunnel measurements. Data from runs on the 6L-71T engine at 1600 rpm agreed quite well between ERC and tunnel methods, but at 2100 rpm the ERC data ran from 45 percent to 80 percent of the tunnel data. Problems with the ERC sampler which are likely causes of the disagreements noted are deposition of particles in the sample line and venturi, inability to sample isokinetically due to lack of control range, and inability to balance sample and primary dilution flows due to lack of control range. For these reasons, further analysis of ERC data in fuel specific or brake specific terms was not considered.

Although all the average particulate concentration data are given in Tables E-2 and E-4, the results for composite runs are restated as Table 18 for convenience. Here the values for the two engines appear to agree more closely than in the specific data, but it should be noted that the exhaust volume per unit work from the 6L-71T is much larger than that from the NTC-290 due to the blower-scavenged 2-stroke design of the former.

TABLE 18. COMPOSITE PARTICULATE CONCENTRATION DATA FROM TWO ENGINES OPERATED ON SIX FUELS, 47mm GLASS FIBER FILTERS

Engine	mg particulate per standard m^3 exhaust gas by fuel					
	A	B	C	A+	B+	C+
6L-71T	59.	65.	59.	61.	129.[a]	67.[a]
NTC-290	28.	48.	36.	27.	61.	39.

[a] these data may be representative of an engine with one or more malfunctioning injectors

E. Constituents of Particulate

Several analyses were conducted to determine particulate composition, and they will be outlined in this subsection. Analyses run specifically on the organic solubles found in particulate samples will be presented in the next subsection.

1. Carbon, Hydrogen, Nitrogen, and Sulfur by Combustion

In order to determine the gross composition of diesel particulate, samples were analyzed for C, H, N, and S by commercial laboratory. The data resulting from these analyses are presented as Tables 19 and 20, and a great deal of useful information can be obtained by examining them. Perhaps the most interesting and most obvious trends in the data are the large differences in carbon/hydrogen ratio between the two engines and the distinct drop in total measureable constituents from fuels B and C to fuels B+ and C+. It is assumed that the percentage by which the sums fall short of 100.0 represent the fraction of particulate which exists as ash, metals, and possibly other substances.

To quantify the above observations to some extent, Table 21 has been prepared to show the average percentage of C, H, N, and S in particulates for each engine and each fuel. The average carbon/hydrogen ratio by mass for untreated fuels (no extra additives) was about 6.8 for the Detroit Diesel 6L-71T, and about 15 for the Cummins NTC-290. This difference means that the particulate from the 6L-71T was mostly a hydrocarbon-like material (n-C_{16} has a carbon/hydrogen ratio of about 5.6), and that particulate from the NTC-290 was more a carbon- (or soot-) like material. The difference was also confirmed by the appearance of filters collected. To document the effect of the metal-containing additive (used in B+ and C+), the average total particulate fractions made up of C, H, N, and S were reduced 20% for the 6L-71T and 39% for the NTC-290 when additive-containing fuels B+ and C+ were used in place of fuels B and C. The difference in reductions is mostly traceable to the difference in basic particulate rates from the two engines, and the reductions themselves to the presence of metals and (possibly) ash on the filters.

2. Analysis for Total Organic Solubles in Particulate

Organic solubles were extracted from particulate samples collected on rectangular (8 inch by 10 inch) glass fiber filters by the Soxhlet technique. The extractions were performed in methylene chloride, benzene, or hexane for a period of four hours with refluxing at 20 cycles per hour. Following extraction, the solvent was evaporated to permit determination of the weight of soluble material present. Ultrasonic ex-

TABLE 19. ANALYSIS FOR CARBON, HYDROGEN, NITROGEN, AND SULFUR IN PARTICULATE SAMPLES, DETROIT DIESEL 6L-71T ENGINE

Operating condition	Weight % - fuel "A"					Weight % - fuel "B"				
	C	H	N	S	∑%	C	H	N	S	∑%
Idle	53.7[a]	7.3	b	b	61.0[a]	60.9	7.7	b	3.0	71.6
1600 rpm - 0% load	70.4	11.3	b	b	81.7	69.1	10.3	1.0	2.1	82.5
1600 rpm - 25% load	81.1	12.6	b	b	93.7	76.8	12.8	1.0	2.6	93.2
1600 rpm - 50% load	72.9	11.1	b	b	84.0	63.5	10.9	b	2.9	77.3
1600 rpm - 75% load	71.2	9.5	b	0.2	80.9	71.1	10.5	0.3	2.1	84.0
1600 rpm - 100% load	69.6	6.3	0.5	b	76.4	66.7	8.8	0.8	2.3	78.6
2100 rpm - 0% load	71.2	10.9	b	b	82.1	66.6	9.8	0.8	1.8	79.0
2100 rpm - 25% load	64.8	10.4	b	b	75.2	65.9	10.4	b	2.8	79.1
2100 rpm - 50% load	75.1	11.8	b	0.4	87.3	65.8	9.8	b	2.4	78.0
2100 rpm - 75% load	70.8	11.4	b	3.9	86.1	69.9	a	b	1.6	a
2100 rpm - 100% load	70.8	9.7	b	1.1	81.6	70.7	10.9	0.4	2.2	84.0
Composite	64.9	10.5	b	1.0	76.4	71.8	10.0	0.3	2.0	84.1

Operating condition	Weight % - fuel "C"					Weight % - fuel "A + additive"				
	C	H	N	S	∑%	C	H	N	S	∑%
Idle	68.4	9.1	b	2.1	79.6	71.4	11.8	0.1	3.9	87.0
1600 rpm - 0% load	73.3	11.1	0.1	0.7	85.2	65.3	10.4	b	0.6	76.3
1600 rpm - 25% load	----	----	---	---	----	----	----	---	---	----
1600 rpm - 50% load	77.2	10.7	0.3	0.6	88.8	69.3	11.6	0.4	0.8	82.1
1600 rpm - 75% load	----	----	---	---	----	----	----	---	---	----
1600 rpm - 100% load	75.0	a	0.1	0.5	a	62.0	6.2	b	1.3	69.5
2100 rpm - 0% load	72.7	9.7	0.9	1.0	84.3	63.2	10.4	b	0.4	74.0
2100 rpm - 25% load	----	----	---	---	----	----	----	b	---	----
2100 rpm - 50% load	77.6	11.7	0.6	0.6	90.5	73.0	11.9	b	0.7	85.6
2100 rpm - 75% load	----	----	---	---	----	----	----	b	---	----
2100 rpm - 100% load	74.5	12.0	b	0.9	87.4	66.8	10.7	b	0.8	78.3
Composite	75.0	11.3	b	1.7	88.0	67.1	10.3	b	0.8	78.2

Operating condition	Weight % - fuel "B + additive"					Weight % - fuel "C + additive"				
	C	H	N	S	∑%	C	H	N	S	∑%
Idle	67.4	10.8	2.0	5.6	85.8	68.6	11.5	b	6.9	87.0
1600 rpm - 0% load	64.6[c]	7.7[c]	0.2[c]	4.3[c]	76.8	58.3	8.8	b	3.8	70.9
1600 rpm - 25% load	56.8	6.2	0.7	2.0	65.7	----	----	---	---	----
1600 rpm - 50% load	61.5	3.1	0.5	1.5	66.6	57.4	5.3	0.3	1.8	64.8
1600 rpm - 75% load	39.9	4.4	b	5.1	49.4	----	----	b, c	---	----
1600 rpm - 100% load	48.9[c]	3.2[c]	1.8[c]	7.4[c]	61.3[c]	42.3[c]	5.2[c]	---	2.7[c]	50.2[c]
2100 rpm - 0% load	73.3	5.6	0.8	2.9	82.6	58.7	7.4	1.6	3.6	71.3
2100 rpm - 25% load	63.9	2.5	0.7	1.2	68.3	----	----	---	---	----
2100 rpm - 50% load	66.2	3.6	b	2.7	72.5	52.5	7.8	b	2.4	62.7
2100 rpm - 75% load	55.7	3.6	b	4.3	63.6	----	----	---	---	----
2100 rpm - 100% load	51.6	4.2	b	4.9	60.7	45.6	7.1	b	2.1	54.8
Composite	52.8[c]	5.5[c]	0.6[c]	4.7[c]	63.6[c]	50.1[c]	6.6[c]	c	2.7[c]	59.4[c]

[a] Questionable data
[b] Below detectable limit
[c] Average of two runs

TABLE 20. ANALYSIS FOR CARBON, HYDROGEN, NITROGEN, AND SULFUR IN PARTICULATE SAMPLES, CUMMINS NTC-290 ENGINE

Operating condition	Weight % - fuel "A"					Weight % - fuel "B"				
	C	H	N	S	∑%	C	H	N	S	∑%
Idle	82.2	10.0	4.1	2.0	98.1	51.4	4.7	[a]	4.8	60.9
1500 rpm - 0% load	67.9	6.0	4.0	1.2	79.1	54.4	6.1	[a]	4.2	64.7
1500 rpm - 25% load	82.1	6.8	1.4	1.9	92.2	70.2	4.5	[a]	4.3	79.0
1500 rpm - 50% load	90.3	3.4	2.9	1.6	98.2	51.8	3.1	[a]	5.0	59.9
1500 rpm - 75% load	84.3	5.0	0.5	5.5	95.3	58.3	2.4	[a]	6.7	67.4
1500 rpm - 100% load	61.2	2.2	1.6	3.4	68.4	54.6	2.4	[a]	5.9	62.9
2100 rpm - 0% load	70.1	5.5	0.6	4.5	80.7	63.3	3.6	[a]	3.3	70.2
2100 rpm - 25% load	88.6	5.3	0.9	2.2	97.0	70.5	2.8	0.3	3.0	76.6
2100 rpm - 50% load	87.3	3.6	0.5	1.4	92.8	70.2	3.0	[a]	3.3	76.5
2100 rpm - 75% load	72.0	5.4	0.6	1.3	79.3	62.7	2.3	0.5	2.2	67.7
2100 rpm - 100% load	82.2	2.5	[a]	2.7	87.4	61.2	2.1	1.6	5.6	70.5
Composite	69.8	3.2	2.9	5.4	81.3	61.9	2.3	[a]	3.3	67.5

Operating condition	Weight % - fuel "C"					Weight % - fuel "A + additive"				
	C	H	N	S	∑%	C	H	N	S	∑%
Idle	60.3	9.5	3.8	5.7	79.3	71.1	3.1	[a]	9.4	83.6
1500 rpm - 0% load	84.4	9.5	0.5	4.4	98.8	53.8	5.7	[a]	4.5	64.0
1500 rpm - 25% load	77.1	6.8	[a]	4.3	88.2	87.4	3.4	0.9	1.8	93.5
1500 rpm - 50% load	86.0	12.8	[a]	1.1	99.9	45.1	[a]	[a]	1.9	47.0
1500 rpm - 75% load	83.0	6.5	1.6	2.0	93.1	82.6	2.9	0.4	1.3	87.2
1500 rpm - 100% load	75.2	8.6	0.7	4.6	89.1	71.8	1.6	[a]	3.2	76.6
2100 rpm - 0% load	78.3	9.2	[a]	5.4	92.9	81.3	4.6	0.5	2.1	88.5
2100 rpm - 25% load	79.3	5.5	[a]	0.9	85.7	88.0	3.3	0.3	1.3	92.9
2100 rpm - 50% load	83.9	6.1	0.6	3.0	93.6	83.6	2.9	1.8	2.1	90.4
2100 rpm - 75% load	84.9	6.0	0.3	2.2	93.4	85.0	2.3	1.4	1.3	90.0
2100 rpm - 100% load	88.2	7.5	0.5	3.2	99.4	84.0	2.2	2.3	1.7	90.2
Composite	85.4	9.0	2.3	3.1	99.8	70.2	2.7	[a]	2.7	75.6

Operating condition	Weight % - fuel "B + additive"					Weight % - fuel "C + additive"				
	C	H	N	S	∑%	C	H	N	S	∑%
Idle	48.0	4.5	0.3	7.5	60.3	42.9	4.2	0.8	5.2	53.1
1500 rpm - 0% load	37.8	4.8	5.4	8.5	56.5	59.1	4.9	6.5	3.9	74.4
1500 rpm - 25% load	34.1	2.7	1.2	8.1	46.1	40.8	2.9	2.2	1.6	47.5
1500 rpm - 50% load	34.2	2.5	1.6	7.1	45.4	46.9	2.8	2.4	1.6	53.7
1500 rpm - 75% load	32.9	2.0	1.7	8.0	44.6	36.4	1.4	1.5	1.4	40.7
1500 rpm - 100% load	17.3	2.1	1.2	9.0	29.6	30.2	1.4	2.8	1.6	36.0
2100 rpm - 0% load	47.8	3.7	1.4	6.1	59.0	52.4	3.9	3.0	2.1	61.4
2100 rpm - 25% load	38.1	2.5	1.0	4.0	45.6	57.6	2.2	1.9	1.5	63.2
2100 rpm - 50% load	31.3	2.4	1.2	6.8	41.7	39.7	2.7	2.1	1.6	46.1
2100 rpm - 75% load	20.6	1.7	0.8	8.9	32.0	35.4	1.5	0.9	1.6	39.4
2100 rpm - 100% load	17.1	1.1	1.1	10.6	29.9	27.2	2.4	2.0	2.4	34.0
Composite	34.6	3.6	1.7	8.5	48.4	73.2	5.1	6.3	3.0	87.6

[a] Below detectable limit

TABLE 21. AVERAGE PERCENTAGE OF C, H, N, AND S IN PARTICULATE BY ENGINE AND FUEL

Engine	Fuel	Average weight % by constituent				
		C	H	N	S	Σ
Detroit Diesel 6L-71T	A	69.7	10.2	0.1	0.6	80.5
	B	68.2	10.2	0.4	2.3	81.1
	C	74.2	10.8	0.2	1.0	85.3
	A+	67.3	10.4	0.1	1.2	79.0
	B+	58.6	5.0	0.6	3.9	68.1
	C+	54.2	7.5	0.2	3.2	65.1
Cummins NTC-290	A	78.2	4.7	1.7	2.8	87.4
	B	60.9	3.3	0.2	4.3	68.7
	C	80.5	8.1	0.9	3.3	92.8
	A+	75.3	2.9	0.6	2.8	81.6
	B+	32.8	2.8	1.6	7.8	45.0
	C+	45.2	3.0	2.7	2.3	53.2

traction was evaluated also, but it did not show any improvement over the Soxhlet technique. Data on organic solubles as percent of total particulate is presented in Table 22 by engine, fuel, and operating condition.

The data in Table 22 show that the percentage of organic solubles in particulate is considerably higher for the 6L-71T than for the NTC-290. This is an expected result, given the carbon and hydrogen percentages in the particulate samples discussed earlier. No trend of percentage organic solubles as a function of operating condition is readily obtainable from the data on the 6L-71T, but it appears that this percentage tended to decrease with increasing load for the NTC-290. No distinct trend of percentage organic solubles as a function of fuel is apparent for either engine.

3. Metals in Particulate by X-ray Fluorescence

As described in an earlier section, X-ray fluorescence was used to analyze samples on Fluoropore filters for 10 metals. The results of all 112 determinations are presented in full in Appendix F, pages F-2 through F-5. The only metal found consistently in nearly all the samples was zinc, normally at levels of about 1 microgram per cm^2 on the filters, which translates to an emission rate of perhaps 1 g/hr or less. The most interesting results were for those samples taken while the engines were operated on fuels containing the organo-metallic additive (fuels B+ and C+). For these tests we have both the metal input to the engine (in the fuel) and the metal output in the particulate, so a material balance can be attempted. A summary of these results is given in Table 23, and although the agreement between metals collected and metals in the fuels

TABLE 22. ORGANIC SOLUBLES AS PERCENT OF TOTAL PARTICULATE

Condition											
rpm	Load, %	Engine	Fuel	Percent solubles	Fuel	Percent solubles	Engine	Fuel	Percent solubles	Fuel	Percent solubles
idle	---	6L-71T	A	36.	A+	58.	NTC-290	A		A+	9.0
PT[a]	0								10.		18.
PT	50			72.		20.			8.1		10.
PT	100			31.					7.0		----[c]
rated	0								22.		13.
rated	50								16.		16.
rated	100								3.9		12.
Composite				55.[b]		54.[b]			3.3[b]		8.1[b]
idle	---		B	37.[b]	B+			B	15.	B+	29.
PT	0			48.					34.		25.
PT	50			50.					4.5		15.
PT	100								0.91[b]		8.7
rated	0								12.		13.
rated	50								7.3		9.1
rated	100			32.[b]					1.8		----[c]
Composite				47.[b]		24.[b]			6.0		7.2[b]
idle	---		C	47.[b]	C+			C	9.9	C+	----[c]
PT	0			64.					16.		9.2
PT	50			52.[b]					7.4		1.6
PT	75			48.							
PT	100			32.					2.8		3.5
rated	0			57.					14.		16.
rated	25			55.							
rated	50			76.					16.		12.
rated	75			73.							
rated	100			67.					-----[c]		1.3
Composite				64.[b]		14.[b]			2.4		7.0

[a] Manufacturer's peak torque speed; 1600 rpm for 6L-71T and 1500 rpm for NTC-290

[b] Average of two or more determinations

[c] Too small to measure

TABLE 23. MATERIAL BALANCES FOR METALS IN ORGANO-METALLIC SMOKE - SUPPRESSANT ADDITIVE, FUELS B+ AND C+

Engine	Fuel	Condition		Calcium, g/hr		Barium, g/hr	
		rpm	%load	Metal in fuel	Metal collected	Metal in fuel	Metal collected
6L-71T	B+	idle	-----	0.34	0.07	0.07	-----[a]
		1600	0	2.0	1.0	0.38	-----[a]
		1600	0	2.1	1.8	0.40	-----[a]
		1600	50	8.8	11.	1.7	1.5
		1600	100	16.	19.	3.0	3.0
		1600	100	15.	18.	3.0	2.1
		2100	0	3.7	4.9	0.71	-----[a]
		2100	50	11.	14.	2.1	1.6
		2100	100	19.	23.	3.6	2.4
		composite		9.0	14.	1.7	3.4
		composite		9.2	11.	1.8	2.7
	C+	idle	-----	0.35	0.57	0.07	-----[a]
		1600	50	8.4	8.3	1.6	1.7
		2100	100	18.	25.	3.5	3.6
		composite		9.0	12.	1.7	2.2
		composite		9.1	7.4	1.8	1.1
NTC-290	B+	idle	-----	0.70	0.45	0.13	0.07
		1500	0	2.4	2.3	0.45	0.44
		1500	50	8.5	7.7	1.6	1.3
		1500	100	16.	16.	3.1	2.8
		2100	0	3.9	4.2	0.75	0.73
		2100	50	12.	12.	2.2	1.9
		2100	100	20.	20.	3.8	3.0
		composite		8.4	3.6	1.6	-----[a]
		composite		8.3	9.4	1.6	1.7
	C+	idle	-----	0.59	0.33	0.11	0.05
		1500	0	2.1	2.1	0.40	0.39
		1500	50	8.4	7.9	1.6	1.3
		1500	100	16.	13.	3.1	1.8
		2100	0	4.0	4.3	0.78	0.83
		2100	50	12.	-----[a]	2.2	1.9
		2100	100	20.	19.	3.8	2.9
		composite		8.2	11.	1.6	2.0
		composite		8.2	12.	1.6	2.1

[a] no data

is not perfect, a good correlation certainly exists. It should be noted that barium and calcium have the highest minimum detectable limits of the ten metals analyzed for, due to optimization of the detection parameters for heavier metals (see page A-2). If the X-ray system were optimized for calcium and barium, the results could be expected to have smaller variability.

To document the relationships between metals in fuel and metals collected, regression equations have been computed for both engines and both fuels as follows:

metal collected = $a_o + a_1$ (metal in fuel)

Engine	Fuel	Metal	a_o	a_1	r^2
6L-71T	B+	Ca	-0.19	1.25	0.980
		Ba	0.17	0.83	0.575
	C+	Ca	-1.83	1.39	0.930
		Ba	-0.09	1.04	0.778
NTC-290	B+	Ca	-0.60	1.01	0.935
		Ba	0.10	0.82	0.976
	C+	Ca	1.21	0.89	0.897
		Ba	0.35	0.67	0.789

Perfect correlations would have r^2 of 1.0, $a_o = 0$, and $a_1 = 1.0$.

Expressed in terms of percentage of total particulates for runs on fuels B+ and C+, metals increased with engine power output, which in turn increased with engine fuel rate. Calcium ranged from about 3 percent to 17 percent of total particulate for the 6L-71T engine and constituted about 8 percent to 29 percent of total particulate for the NTC-290 engine (slightly higher percentages for fuel C+ than for fuel B+). Barium constituted about 1 percent to 2 percent of particulate for the 6L-71T engine and some 1 percent to 4 percent of particulate for the NTC-290 (again slightly higher for fuel C+ than for fuel B+).

4. Phenols and Nitrosamines

In summary, no nitrosamines were found in the samples submitted for analysis to a detection limit of 0.1μg on a hi-vol filter. In terms of particulate quantity, this limit means that if nitrosamines were present, they constituted less than 1 x 10^{-3}% of particulate in all cases and less than 1 x 10^{-4}% of particulate for typical cases. Due to filter backgrounds, phenols found were in such quantity that no real credibility can be attached to their existence in particulate samples. Of the 9 phenols analyzed, no trace of 2,6 xylenol or 3,4 xylenol was found in any sample. Quantities of other phenols were essentially traces, in no case more than 1 μg on a filter (or $1 \times 10^{-3}\%$ of particulate collected). Twenty samples from runs on the 6L-71T were analyzed, and 21 samples from the NTC-290 were analyzed, in addition to a number of blanks.

F. Constituents of Organic Soluble Fraction of Particulate

A variety of analyses were conducted on organic solubles, and they will be presented separately for clarity.

1. Carbon, Hydrogen, Nitrogen, Sulfur, and Oxygen by Combustion

The gross composition of the organic soluble fraction of a number of diesel particulate samples was determined by a commercial laboratory using combustion analysis. The samples submitted were a part of those used in the BaP analysis and for NMR and IR spectral analysis, and most of them were quite small (10 to 100 mg). In a number of cases, sample size was not sufficient for oxygen determination, and sufficient for only a rudimentary sulfur determination. The number of samples submitted for analysis was limited because relatively few of them contained enough sample for a proper analysis (15 mg was the nominal lower limit for a complete analysis).

Data on composition of organic solubles are presented in Table 24 for all the samples submitted. No samples from runs on fuels B+ or C+ were submitted because metals supposedly create an interference with the oxygen measurements.

The most obvious conclusion to be reached about the data in Table 24 is that they are highly indicative of a hydrocarbon-type material with relatively small amounts of nitrogen, sulfur, and oxygen. The average carbon/hydrogen ratio by weight for the solubles from the 6L-71T engine was 6.5, and that for the solubles from the NTC-290 engine was 7.1. For comparison, the carbon/hydrogen ratio by weight of n-$C_{16}H_{34}$ is 5.65. Although lack of accuracy in oxygen measurement restricts the strength of conclusions to be drawn, it appears that surprisingly little oxygen was present in the organic solubles. The presence of oxygenated compounds was detected in a few of the samples by spectral analysis, as will be discussed in a later subsection.

2. Paraffin Boiling Point Distribution

Boiling point distributions have been obtained for a number of samples of organic solubles in the range of 230 to 540°C (450 to 1000°F) by gas chromatograph. Most of the samples have been run both "as extracted" and as paraffins only (following fractionation). In general, the boiling point distribution of the paraffins recovered followed that of the total solubles

TABLE 24. CARBON, HYDROGEN, NITROGEN, SULFUR, AND OXYGEN IN THE ORGANIC SOLUBLES OF DIESEL PARTICULATE

		Condition		Percent by weight in organic solubles					
Engine	Fuel	rpm	load, %	C	H	N	S	O	∑%
D.D. 6L-71T	A+	1600	50	86.	13.	0.1	0.1	0.2	99.+
		composite		85.	13.	0.1	0.1	---	98.+
	B	idle	---	86.	13.	0.2	0.3	0.7	100.
		1600	50	83.	13.	0.4	0.2	3.4	100.
		2100	100	79.	12.	0.7	0.2	8.4	99.+
		composite		82.	12.	0.2	0.8	4.5	99.+
	C	idle	---	85.	13.	0.1	0.1	---[a]	98.
		idle	---	85.	13.	0.1	0.1	---[a]	98.
		1600	50	86.	13.	0.1	0.2	0.6	100.
		1600	75	85.	13.	0.1	0.2	---[a]	98.
		2100	0	85.	13.	0.2	0.4	---[a]	99.+
		2100	75	86.	14.	0.0	0.1	---[a]	92.
		composite		80.	12.	0.4	0.1	---[a]	85.
NTC-290	A	2100	50	70.	11.	3.6	---[b]	---[a]	82.
	A+	1500	50	71.	11.	0.1	---[b]	---[a]	96.
		2100	0	83.	12.	1.1	---[b]	---[a]	82.
	B	idle	---	72.	8.7	0.8	---[b]	---[a]	94.
		1500	0	83.	11.	0.1	---[b]	---[a]	97.
		2100	0	84.	12.	0.6	---[b]	---[a]	97.
		2100	50	83.	12.	0.5	---[b]	---[a]	96.
	C	2100	50	78.	11.	0.0	---[b]	---[a]	89.

[a] insufficient sample for oxygen determination

[b] sulfur under 0.5%, insufficient sample for more precise determination

recovered; although in most cases, each percentile of the paraffins occurred a few degrees above the total solubles. Differences occurred, however, in total boiling range relative to the original amount of solubles present due to differences in recovery (solubility and boiling range) between samples.

The appearances of the GC output from several calibration and sample runs are shown in Appendix A, Figures A-15 through A-21. Figures A-15 and A-16 show calibrations of the system with pure normal paraffins, producing strong peaks with baseline separation. Figure A-17 shows one of the fuels used for testing (fuel A), indicating strong presence of normal paraffins but also a "hump" consisting primarily of overlapping aromatics, isoparaffins, and cycloparaffins. Figure A-18 is the output from an analysis of the lubricating oil used in the Detroit Diesel 6L-71T engine (same as that used for the NTC-290), indicating few normal paraffins and a much higher boiling range than the fuels. The single small peak between the calibration standards and the oil itself is n-cetane, which was added to the oil at a concentration of about one percent for possible use as a tracer. This peak was not readily identifiable in any of the samples of solubles.

As an aid in the interpretation of the boiling range data, Figure 22 has been prepared with percent by weight (distilled) plotted versus temperature and carbon number of n-paraffins. Solubles from samples taken during operation of the 6L-71T engine, as noted in Figure 22, match the boiling range of the lubricating oil quite closely. Solubles from the NTC-290 engine, however, seem to be composed mainly of material which boils above 500°C. The existing GC analysis simply cannot be extended far enough to reach the higher-boiling materials, so it was possible to characterize only the lighter ends of these materials. The appearance of a typical gas chromatograph output for solubles from the 6L-71T engine is shown as Figure A-19, and a typical output for the NTC-290 engine is shown as Figure A-20.

Figure A-21 shows a particular sample from the NTC-290 engine which has an anomalous peak at about 415°C. The fuel used for this test was "B+ additive", and the engine was running at 1500 rpm and 50 percent load. One other sample was analyzed which had been taken during a run on the same fuel (2100 rpm and 50 percent load), and a peak occurred at the same temperature but had only about 6 percent of the height of the previous peak. It is planned to run a portion of these samples on a GCMS (gas chromatograph-mass spectrometer) for further identification, but that information is not available for this report. The first peak mentioned also resulted in the near-vertical portion of the upper curve for solubles from the NTC-290 engine at about 415°C in Figure 22.

To complete the presentation of data on boiling point distribution of solubles, Table 25 presents numerical information in a fairly comprehensive form. These data, with additional detail as necessary to form continuous plots, are the basis for Figure 22. Distribution of normal paraffin boiling points is given in Figure 22, so it is not considered necessary to duplicate it in Table 25.

3. Analysis for Benzo (α) Pyrene in Organic Solubles

A number of BaP determinations were conducted on samples from both engines and all fuels, and the results showed a considerable amount of unexplained variability. Although various techniques have been used for BaP measurement for a number of years, determination of BaP in diesel particulate is still in its infancy. It is recommended, due to unexplained variability in results and the lack of similar data in the literature, that the BaP results be treated as preliminary and tentative. Projections of emission contributions should not be made using

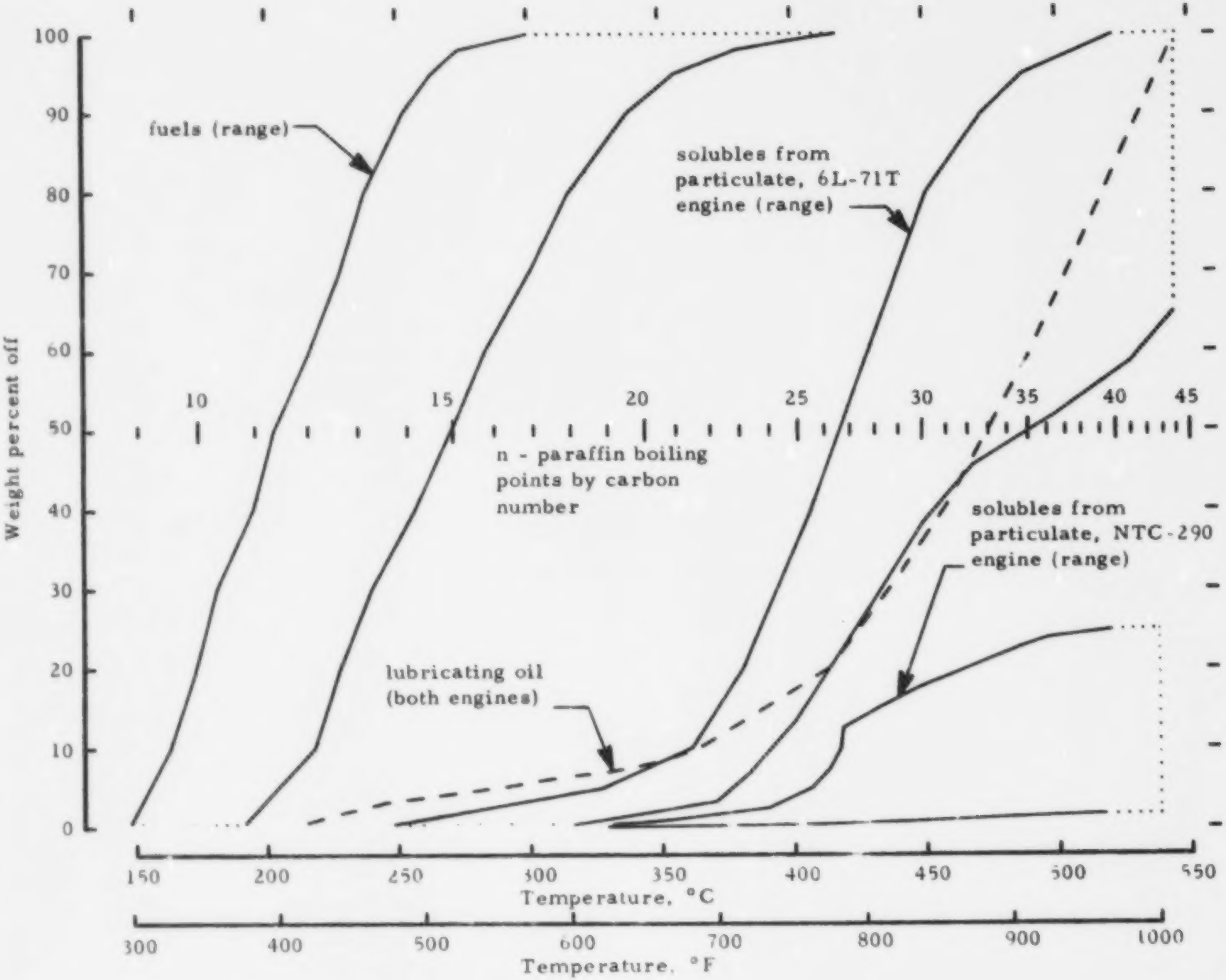


FIGURE 22. BOILING RANGES OF FUELS, LUBRICATING OIL, AND ORGANIC SOLUBLE FRACTIONS OF PARTICULATE FOR BOTH ENGINES USED IN METHODOLOGY DEMONSTRATION

TABLE 25. BOILING POINT DISTRIBUTIONS FOR FUELS, LUBRICATING OIL, AND ORGANIC SOLUBLE FRACTIONS OF PARTICULATE SAMPLES

Sample type	Engine	Fuel	Condition		Recovery, %	Temperature in °C at weight % off							
			rpm	% load		0.5	10	20	40	60	80	90	100
Fuel A (straight)					34	148	163	173	195	217	238	253	301
Fuel B (straight)					64	161	198	217	257	284	316	338	417
Fuel C (straight)					100	191	218	228	237	248	261	274	356
Lubricating oil (straight)					99	215	364	413	457	490	518	532	545
Total solubles	6L-71T	A	1600	50	89	322	391	409	436	466	511	--[c]	--[c]
			comp.	var.	100[a]	284	384	397	419	441	466	491	534
		B	idle	---	100[a]	278	378	391	413	434	456	473	522
			1600	0	100[a]	279	379	392	414	436	462	487	538
		C	idle	---	88	319	385	403	429	451	497	--[c]	--[c]
			1600	0	100[a]	255	364	396	422	453	490	518	545
			1600	50	89	282	386	399	425	447	489	--[c]	--[c]
			1600	50	100[a]	259	369	391	418	449	501	527	546
			1600	100	100[a]	276	375	393	414	432	458	475	523
			2100	25	100[a]	259	378	404	436	470	518	536	545
			2100	100	100[a]	281	363	381	407	429	451	472	529
		A+	idle	---	100[a]	289	385	407	443	484	523	537	546
			comp.	var.	100[a]	287	383	401	428	458	502	524	545
		B+	comp.	var.	89	258	373	395	431	465	529	--[c]	--[c]
	NTC-290	A	1500	0	14.1	364	462	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]
		C	1500	0	5.4	375	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]
			2100	0	7.4	397	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]
			mix[b]		2.9	405	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]
		B+	1500	50	24.8	343	418	465	--[c]	--[c]	--[c]	--[c]	--[c]
			2100	50	12.7	382	473	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]
		C+	1500	0	9.6	341	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]
			mix[b]		9.6	393	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]
Paraffins only	6L-71T	A	1600	50	68	316	397	414	454	516	--[c]	--[c]	--[c]
			comp.	var.	93	291	391	408	434	469	514	533	--[c]
		B	idle	---	94	298	381	398	424	446	492	524	--[c]
			1600	0	100[a]	295	377	395	421	443	477	506	537
		C	idle	---	72	309	392	410	441	487	--[c]	--[c]	--[c]
			1600	0	100[a]	249	362	389	420	446	488	516	545
			1600	50	78	292	388	409	436	478	--[c]	--[c]	--[c]
			1600	50	100[a]	261	371	388	415	446	503	532	546
			1600	100	100[a]	277	381	394	417	434	460	505	533
			2100	25	100[a]	261	389	411	451	506	533	541	545
			2100	100	100[a]	297	367	389	411	437	467	500	532
		A+	idle	---	88	280	388	411	446	499	537	--[c]	--[c]
			comp.	var.	86	285	386	403	439	477	536	--[c]	--[c]
		B+	comp.	var.	65	313	394	417	461	533	--[c]	--[c]	--[c]
	NTC-290	A	1500	0	4.7	374	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]
		C	1500	0	4.5	372	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]
			2100	0	6.6	409	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]
			mix[b]		1.4	429	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]
		B+	1500	50	5.7	381	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]
		C+	1500	0	7.2	400	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]
			mix[b]		5.1	408	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]

[a] value as calculated exceeded 100 percent due to baseline upset

[b] several samples mixed together

[c] out of range of analysis

these data as basis. Thus qualified, average data are presented in Table 26 in terms of milligrams BaP per kilogram fuel consumed. Complete data are given in Appendix G, Tables G-1 and G-2, in terms of milligrams per hour and micrograms per standard cubic meter of exhaust gas.

Several trends are apparent in the data from Table 26, perhaps the most important being the decrease in fuel specific BaP with increasing power (at a given speed) for the Cummins NTC-290 engine. This was a very strong trend, but no confirmation exists for other engines at this point. Analysis of the Cummins NTC-290 data is much more useful than analysis of the 6L-71T data presented, because quite a bit of development in the BaP analysis procedure was still underway when the latter engine was run. The data also indicated higher BaP, in most cases, for samples taken during runs on fuels B+ and C+ than for comparable samples taken during runs on fuels B and C.

Although the comparison must be qualified heavily due to the holes in the 6L-71T data, it appears at this point that BaP emissions from the 6L-71T engine were considerably higher than from the NTC-290. The average fuel specific BaP result from composites run on the 6L-71T was 0.68 mg/kg fuel, while that from the NTC-290 was 0.21 mg/kg fuel. In brake specific terms, these averages of composite data are 180μg/kW hr (130μg/hp hr) for the 6L-71T and 59μg/kW hr (44μg/hp hr) for the NTC-290. If the lubricating oil acts as a "sink" for BaP, both the fact that the 6L-71T's particulate seemed more oily than that from the NTC-290 and the longer overall operating time for the 6L-71T are possible (partial) explanations for the apparent difference between engines.

4. NMR and IR Spectra of Organic Solubles

Peaks of significant proportion, other than those denoting hydrocarbon chains, were noted on 14 of the 93 NMR spectra. These peaks may also have been present in other spectra, but some of the samples were unavoidably too dilute (due to small amount of solubles) to obtain a proper signal. The peaks noted fall generally into three categories by chemical shift as follows:

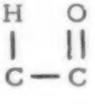
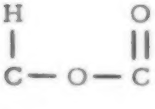
δ, ppm	Proton location	Grouping
1.8	 $\overset{\overset{H}{\vert}}{C}-\overset{\overset{O}{\Vert}}{C}$	carbonyl
4.2, 4.8	 $\overset{\overset{H}{\vert}}{C}-O-\overset{\overset{O}{\Vert}}{C}$	ester
7.5	$R-\phi-H$	benzene ring

TABLE 26. AVERAGE FUEL SPECIFIC BaP RESULTS

Condition											
rpm	load, %	Engine	Fuel	BaP, mg/kg fuel	Fuel	BaP, mg/kg fuel	Engine	Fuel	BaP, mg/kg fuel	Fuel	BaP, mg/kg fuel
idle	-	6L-71T	A	0.18	A+	1.4	NTC-290	A	0.25	A+	0.06
PT[a]	0								0.30		0.38
PT	50			0.086		0.70			0.047		--[c]
PT	100			0.28					0.027		--[c]
rated	0								0.20		--[c]
rated	50								0.20		0.13
rated	100								0.090		--[c]
composite				0.17[b]		0.54[b]			0.060[b]		0.039[b]
idle	-		B	2.4[b]	B+			B	0.40	B+	0.83
PT	0			5.1					0.47		0.52
PT	50			0.22					0.014		0.17
PT	100								0.022[b]		0.17
rated	0								0.46		1.9
rated	50								0.073		0.21
rated	100			0.47[b]					0.049		0.11
composite				0.53[b]		0.94[b]			0.19		0.40[b]
idle	-		C	4.9[b]	C+			C	0.30	C+	0.78
PT	0			1.0					0.52		1.2
PT	50			0.25[b]					0.014		0.14
PT	75			0.49							
PT	100			0.21					0.018		0.15
rated	0			4.5					0.087		0.55
rated	25			0.99							
rated	50			1.1					0.082		0.39
rated	75			0.62							
rated	100			0.018					0.034		0.27
composite				1.2[b]		0.69[b]			0.14[b]		0.45[b]

[a] manufacturer's peak torque speed; 1600 rpm for 6L-71T and 1500 rpm for NTC-290

[b] average of two or more determinations

[c] not enough to measure

The infrared spectra mostly contained peaks confirming the presence of saturated hydrocarbon chains. In 19 of the 94 IR spectra, a band appeared at 1740 cm^{-1}, indicative of an ester carbonyl. A positive match between IR and NMR spectra occurred for eight samples, with one other instance being probable. Indication of an ester by IR without an NMR match creates no conflict, since NMR is not as sensitive as IR for this grouping. No strong relationships between the occurrence of significant peaks and operating condition, fuel, or engine were noted. Further analysis of these data does not seem appropriate for this report due to the small mass of usable data, but all the spectra and a copy of the analysis summary is being supplied to EPA with this report should further work be recommended.

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APPENDIX A

DETAILS OF ANALYTICAL PROCEDURES

TABLE A-1. MINIMUM DETECTION LIMITS FOR METALS BY ELEMENT AND FILTER BATCH

Filter batch(es)	Sample numbers	Minimum detection limit, $\mu g/cm^2$				
		Ca	V	Mn	Ni	Cu
1 and 2	1-38	0.90	0.16	0.20	0.08	0.07
3	39-54	0.41	0.11	0.13	0.05	0.05
4	55-76	0.53	0.11	0.15	0.06	0.07
5	77-94	0.44	0.14	0.15	0.06	0.06
6	95-112	0.38	0.19	0.23	0.09	0.08
	Average	0.53	0.71	0.17	0.07	0.07

Filter batch(es)	Sample numbers	Minimum detection limit, $\mu g/cm^2$				
		Zn	Pb	Sr	Sn	Ba
1 and 2	1-38	0.06	0.22	0.07	0.64	1.22
3	39-54	0.04	0.17	0.05	0.39	1.80
4	55-76	0.05	0.21	0.06	0.54	1.63
5	77-94	0.04	0.20	0.06	0.46	1.31
6	95-112	0.06	0.21	0.05	0.48	1.28
	Average	0.05	0.20	0.06	0.50	1.45

ELECTRON MICROPROBE X-RAY SPECTRUM

Scanning Electron Analysis Laboratories, Inc.
5301 Beethoven Street, Los Angeles, CA 90066

Sample SWRI STD. 0.01 MG Mn, Ni, Cu, Zn, Pb, Sr Area Ident.
Beam Voltage 49.9KV Beam Current 0.2ma Aperture 3mm ~~Tilt Angle~~ FILTER Rh Acquisition Time 300s ~~Scan Rate~~ TUBE Rh
~~Scan Size~~ AIR PATH Notes ON WHATMAN 42 By AK Date 9/10/74

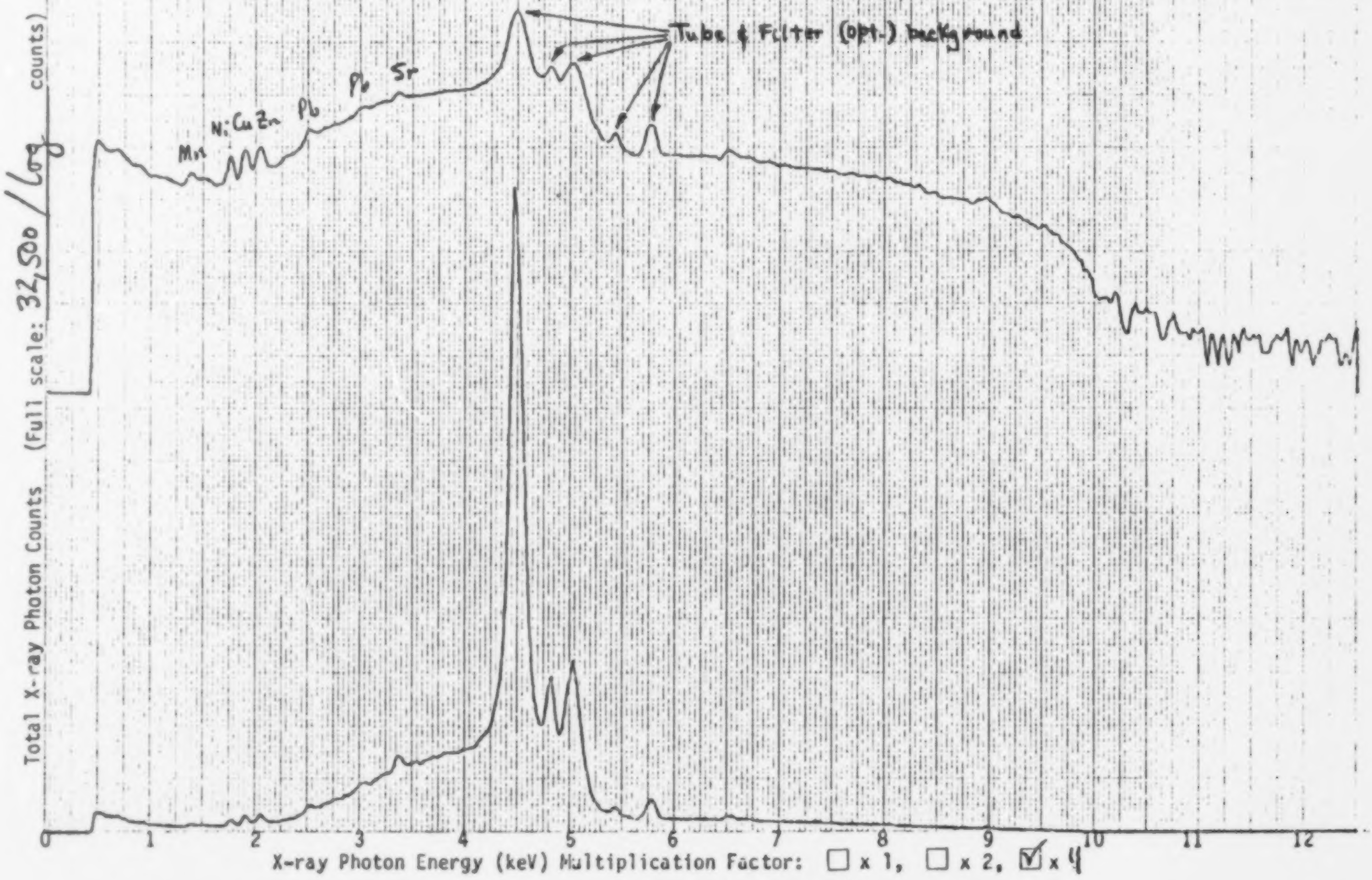


FIGURE A-1. X-RAY SPECTRUM OF SAMPLE STANDARD CONTAINING SEVEN METALS

K E 10 X 10 TO THE CENTIMETER 46 1513
KEUFFEL & ESSER CO.

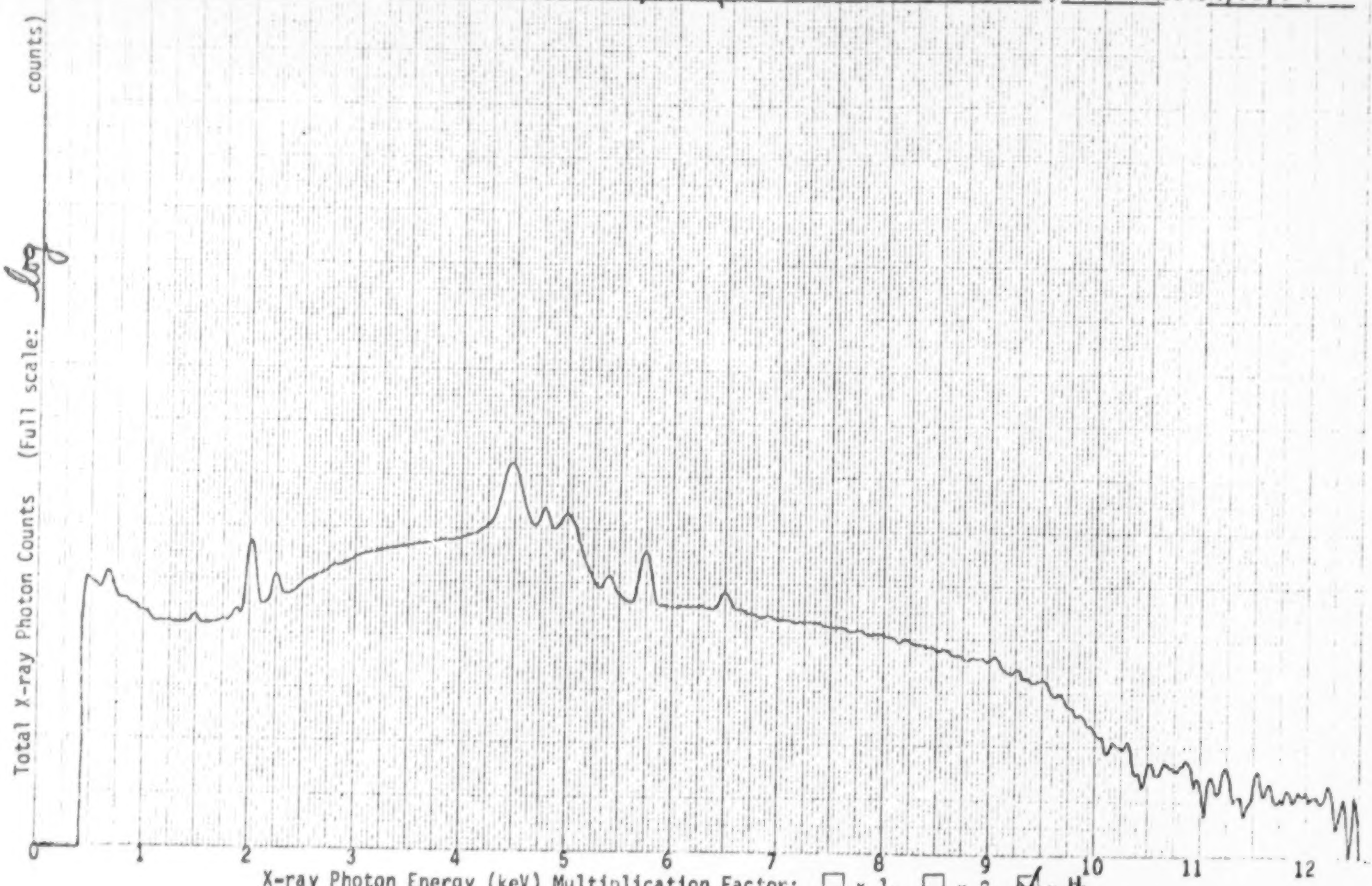
ELECTRON MICROPROBE X-RAY SPECTRUM

Scanning Electron Analysis Laboratories, Inc.
5301 Beethoven Street, Los Angeles, CA 90066

Sample SWRI 5-6 FP47-144 Area Ident.

Beam Voltage 49.9 KV Beam Current 0.8 ma Aperture 3 mm Tilt Angle — Acquisition Time 300 s Scan Rate —

Scan Size — Notes Rh tube and filter; air path By LK Date 9/10/74



Multiplication Factor: ☐ x 1, ☐ x 2, ☑ x 4

FIGURE A-2. X-RAY SPECTRUM OF A DIESEL PARTICULATE SAMPLE

Method for Determination of Phenols and N-Dimethylnitrosamine in Particulate Matter Collected on Glass Fiber Filter

1. Cut filter in pieces approximately 5 x 40 mm and place in 200-ml round bottom distillation flask.
2. Add 70 ml of 1% H_3PO_4 in water.
3. Connect distillation flask to vertically mounted small diameter (8 mm O. D.) water cooled condensing tube. This distillation set-up is similar to a Kjeldahl distillation apparatus.
4. Place 5 ml of 50% KOH in 50 ml beaker and place beaker so that outlet end of condenser tube is immersed in KOH solution.
5. Distill over 35 ml H_2O and rinse condenser tube with 5 ml H_2O. Should now be approximately 45 ml in beaker.
6. Transfer, without rinsing, contents of beaker to 125-ml separatory funnel.
7. Add 13 gm NaCl to funnel and shake to dissolve.
8. Rinse condenser tube with 10 ml benzene and collect in 50 ml beaker.
9. Transfer benzene to separatory funnel containing distillate and shake vigorously for 1 minute.
10. Drain aqueous phase into another 125-ml separatory funnel. Discard benzene.
11. Add 10 ml dichloromethane (DCM) to separatory funnel containing aqueous phase and shake vigorously for 1 minute.
12. Collect DCM in small vial and save.

13. Add 10-ml hexane to separatory funnel and shake well.
14. Drain aqueous phase into 100-ml volumetric flask. Discard hexane.
15. Add 1 drop Phenolphthalein Indicator Solution to aqueous phase.
16. Add concentrated H_3PO_4 to aqueous phase to indicator end-point then add 2-3 drops excess H_3PO_4.
17. Cool to room temperature and add 0.5 ml diisopropyl ether (DIE).
18. Shake vigorously for 1 minute and immediately pour into 50-ml volumetric flask using appropriate funnel.
19. Swirl contents of stoppered flask and then allow DIE to collect on aqueous surface in neck of flask.
20. Insert ground glass stopper, to which has been attached a short length (60 mm) of 2-mm I.D. capillary tubing, into mating glass joint on flask.
21. Using a syringe and needle, inject water into flask through previously inserted silicone plug in flask body, so as to force the DIE up into the capillary tube.
22. Using a micro syringe, withdraw 5μl of DIE and inject into gas chromatograph for analysis of phenols.
23. The DCM previously saved is transfered to a micro concentrator and evaporated down to 0.5-0.75 ml.
24. 20μl of the concentrate DCM extract is injected into a gas chromatograph equipped with an Electrolytic Conductivity Detector used in the pyrolitic mode for selective detection of N-nitrosamines.

CHROMATOGRAPHIC CONDITIONS

Phenols

Column: 6' 10% OV-3 + 1% FFAP on 80-100 mesh Gas-Chrom Q-AWDMS

Column Temp: 125°C

Detector: FID

Detector Lens: 16X

Dimethylnitrosamine

Column: 6' 10% Carbowax 1540 + 10% KOH on 60-80 Gas-Chrom Q

Column Temp: 125°C

Detector: Electrolytic Conductivity (Pyrolytic mode)

Detector Lens: 1X

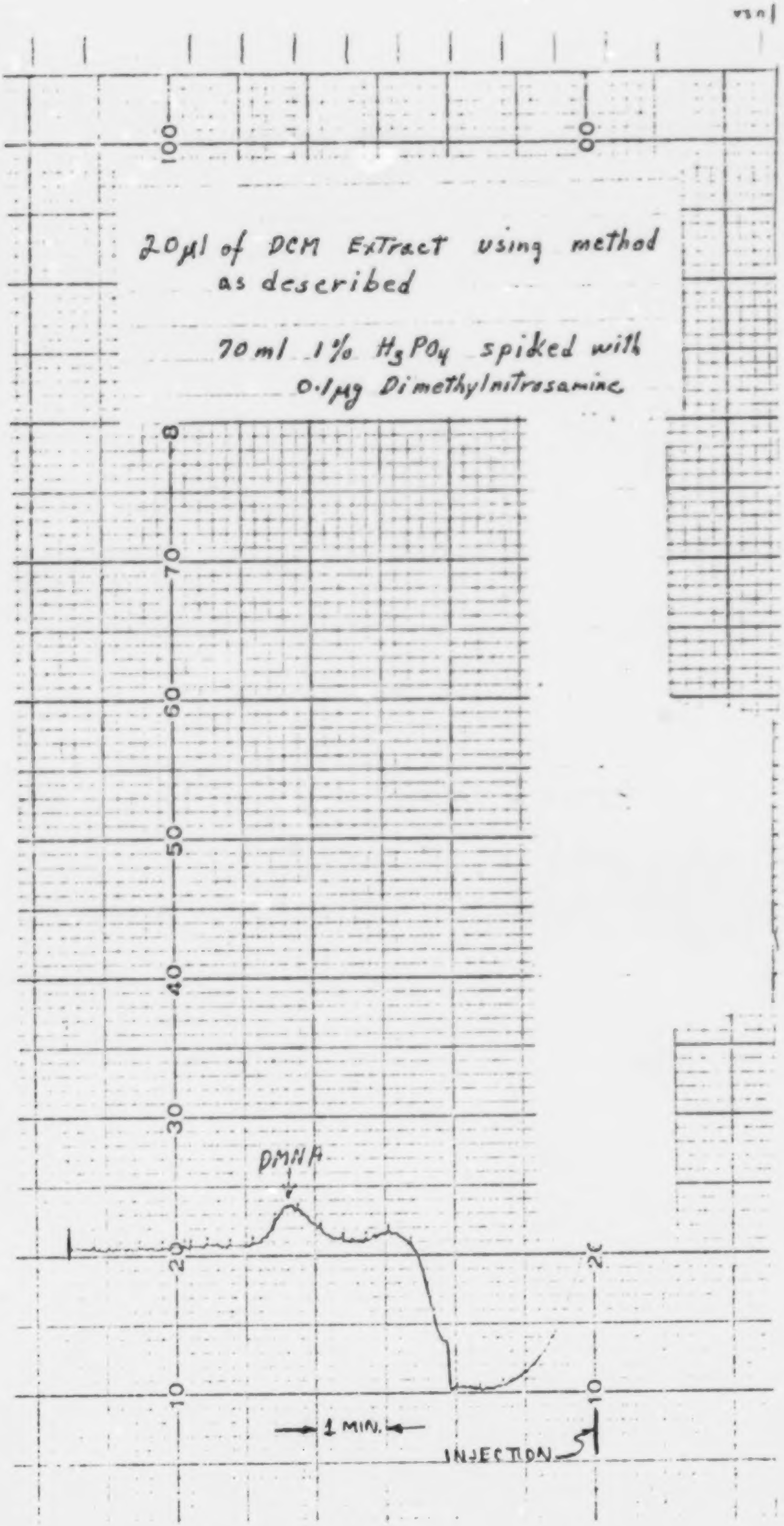
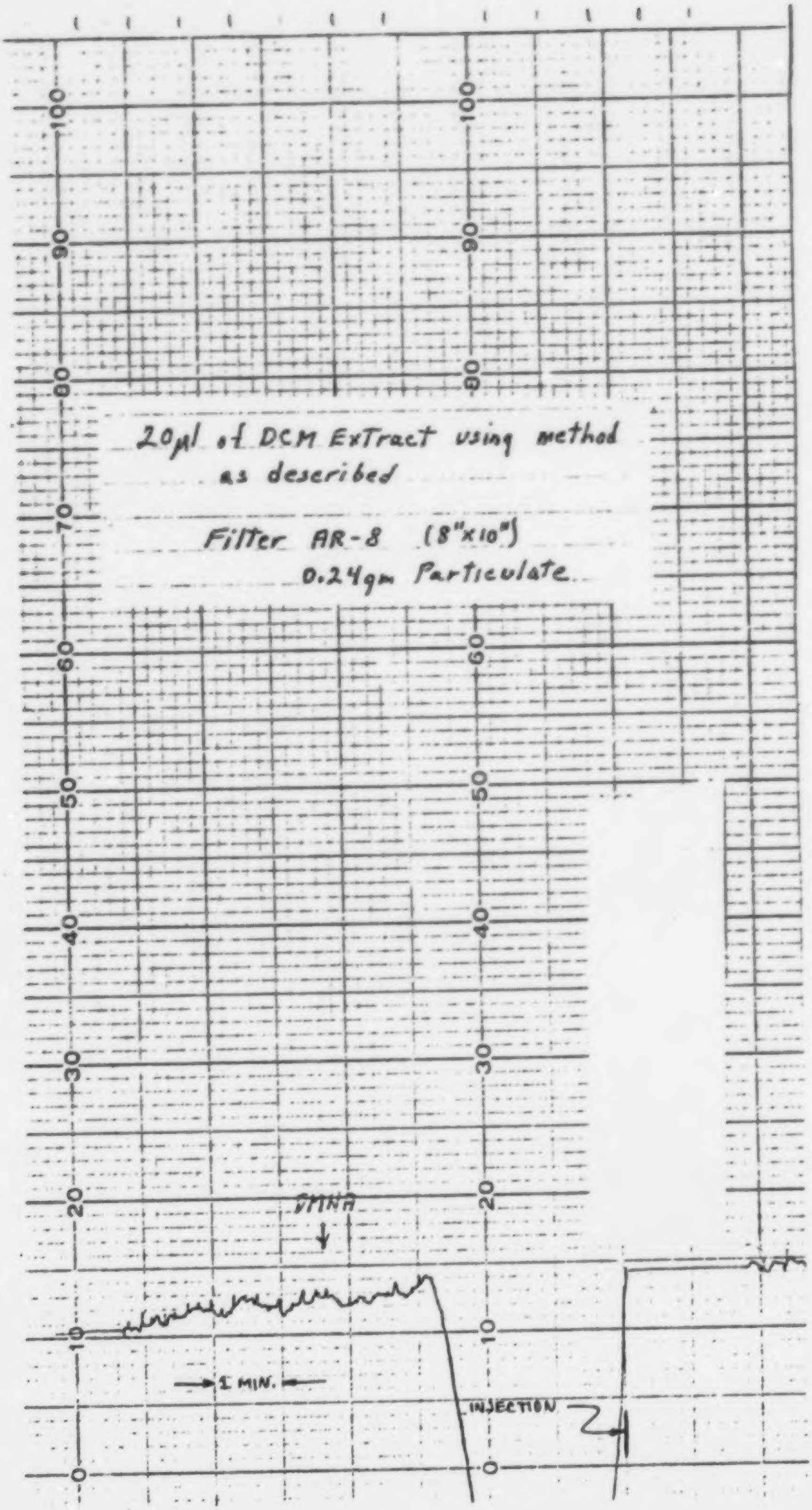


FIGURE A-3. SAMPLE STANDARD DETECTION BY NITROSAMINE ANALYSIS SYSTEM



20µl of DCM Extract using method
as described

Filter AR-8 (8"x10")
0.24gm Particulate

FIGURE A-4. DIESEL PARTICULATE SAMPLE ANALYZED
BY NITROSAMINE DETECTION SYSTEM

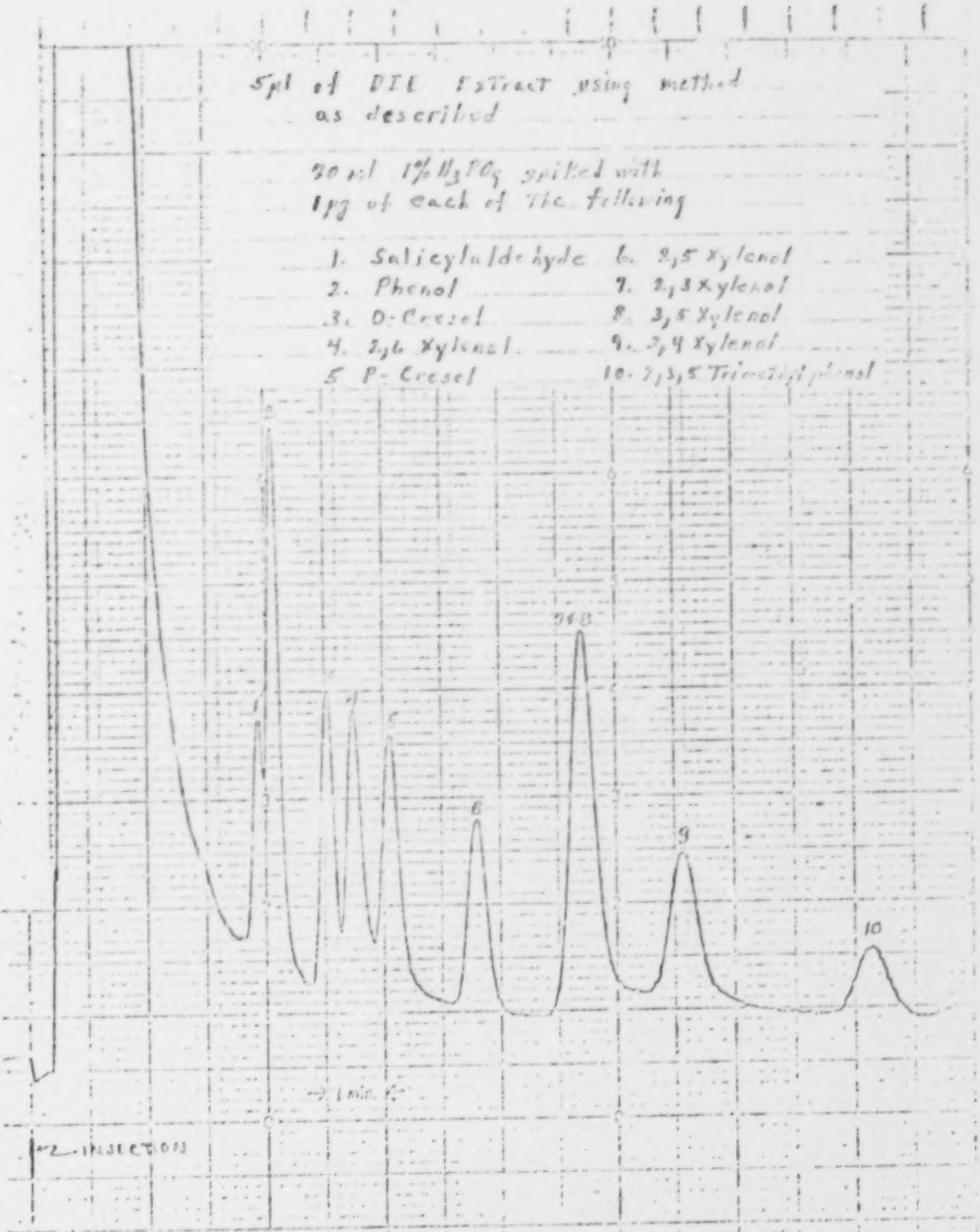


FIGURE A-5. SAMPLE STANDARD ANALYZED BY PHENOL DETECTION SYSTEM

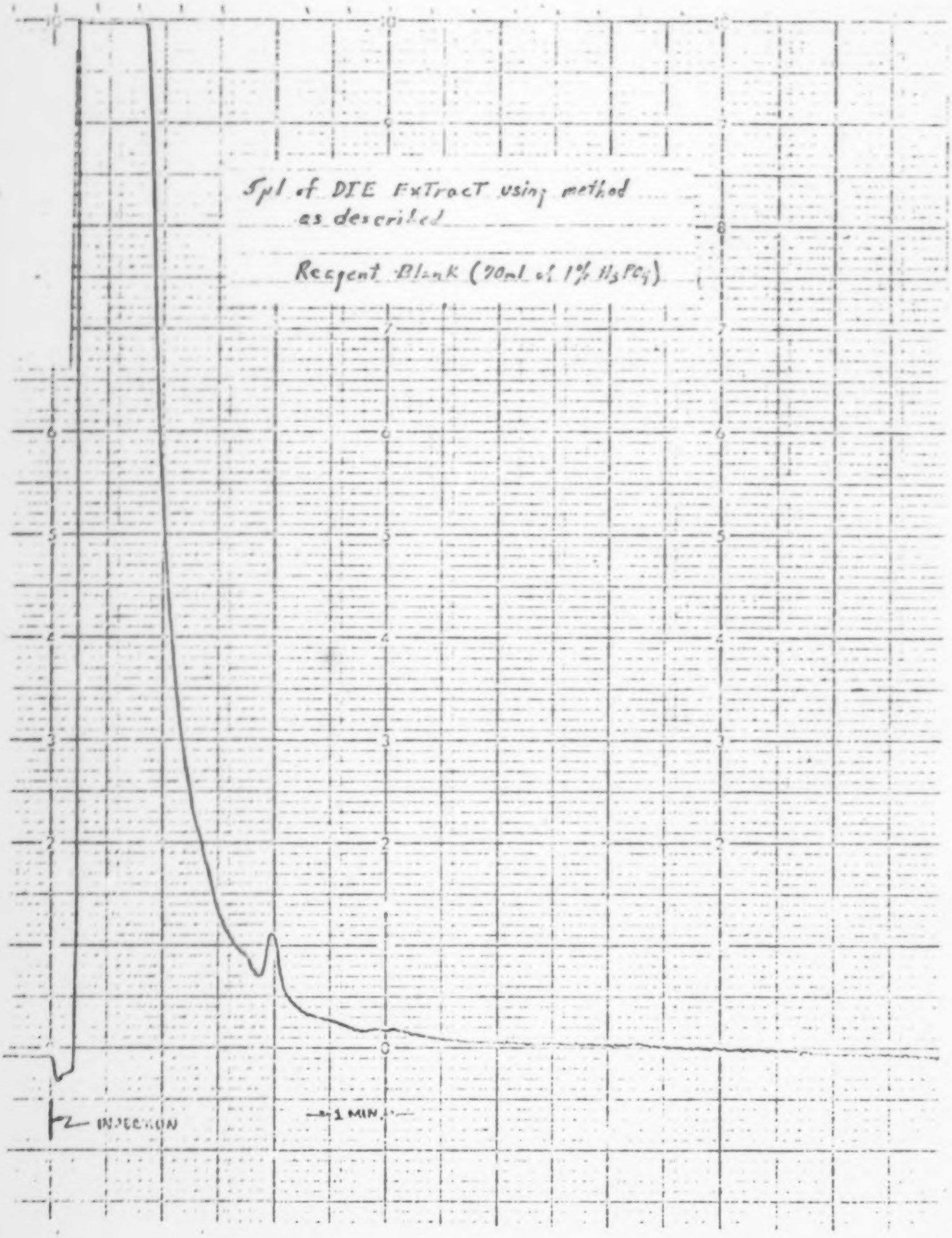


FIGURE A-6. REAGENT BLANK ANALYZED BY PHENOL DETECTION SYSTEM

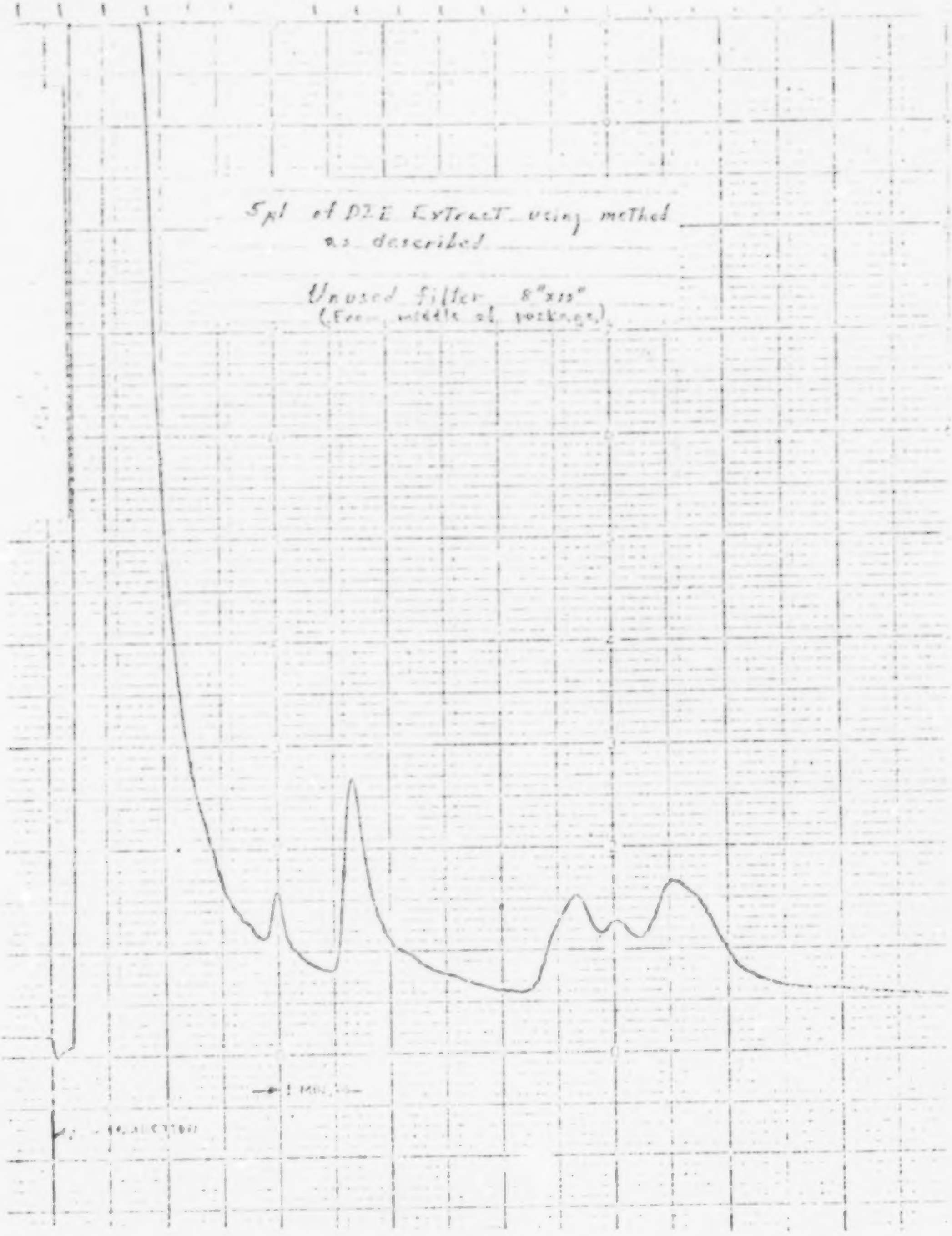


FIGURE A-7. UNUSED GLASS FIBER FILTER ANALYZED BY PHENOL DETECTION SYSTEM

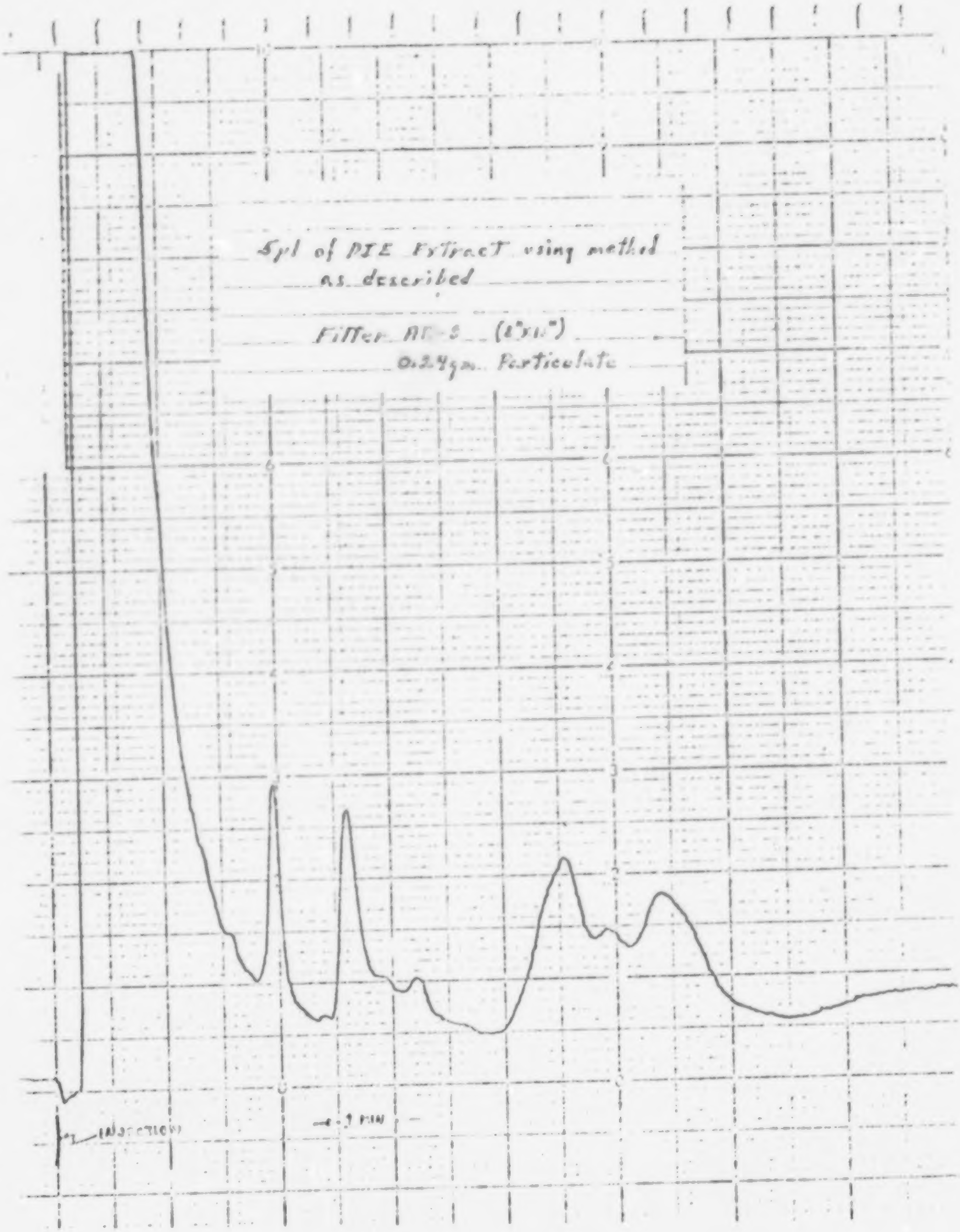


FIGURE A-8. DIESEL PARTICULATE SAMPLE ON GLASS FIBER FILTER ANALYZED BY PHENOL DETECTION SYSTEM

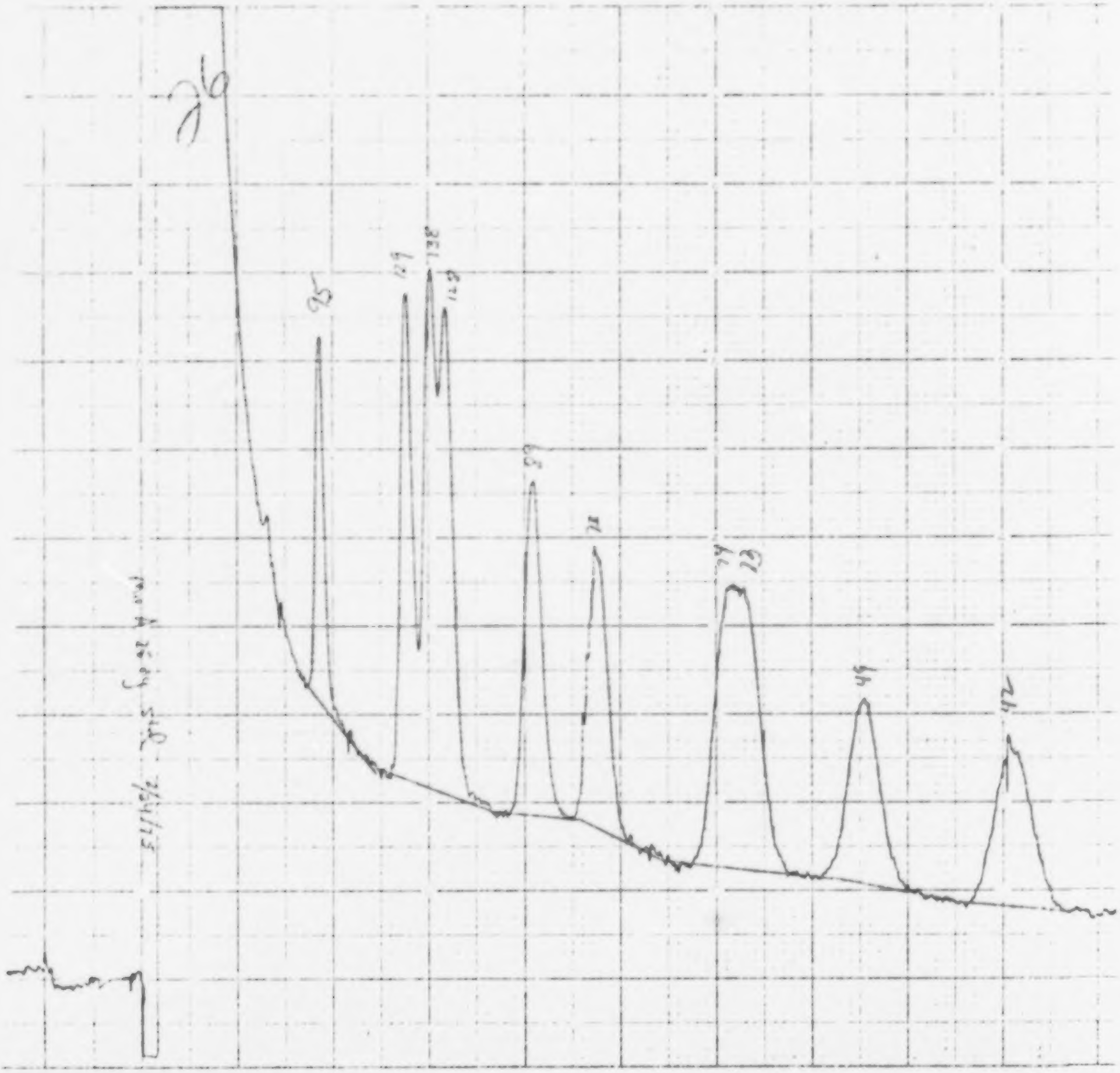


FIGURE A-9. LATER SAMPLE STANDARD ANALYZED BY PHENOL DETECTION SYSTEM

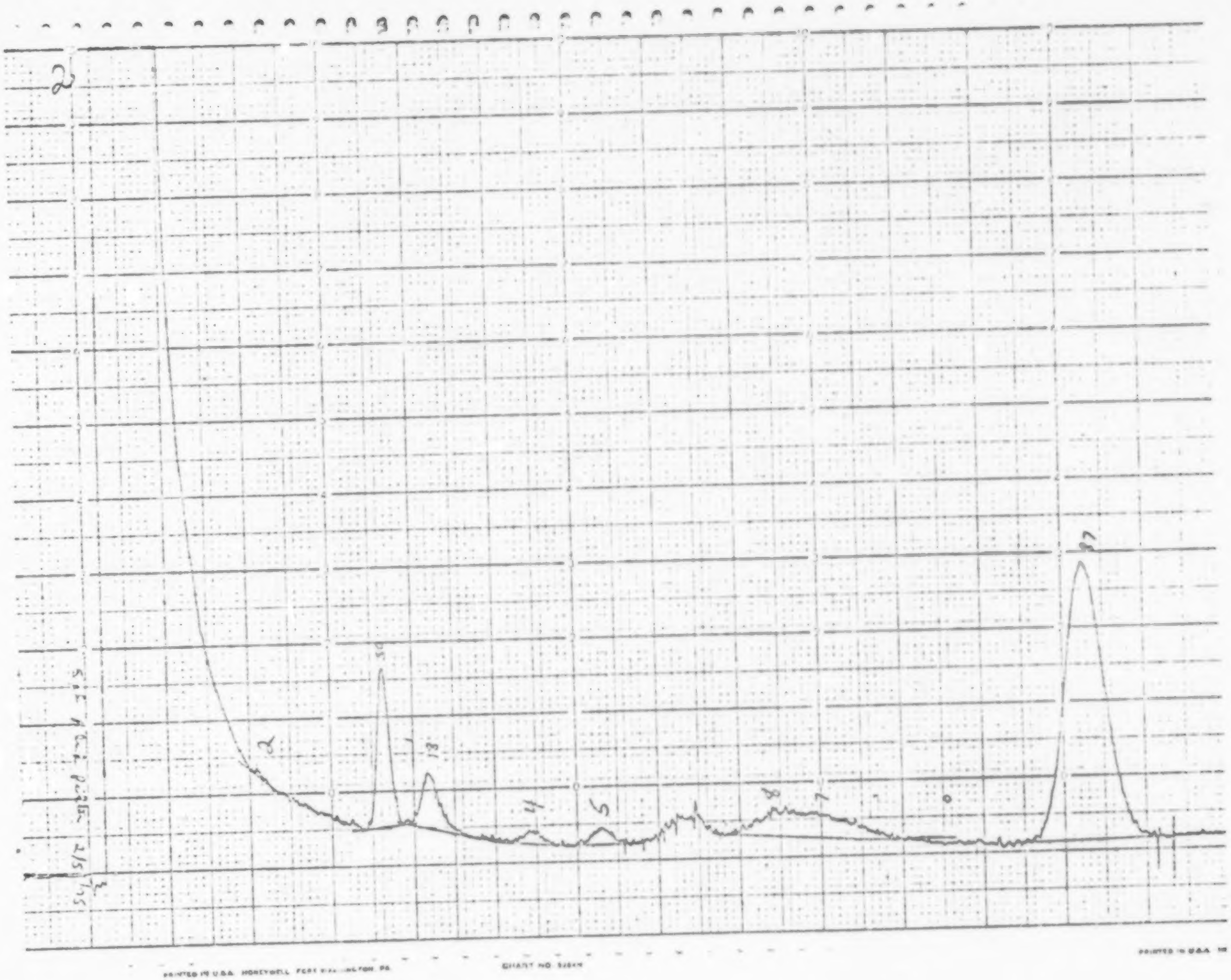


FIGURE A-10. UNUSED FLUOROPORE FILTER ANALYZED BY PHENOL DETECTION SYSTEM (FIRST OF TWO SAMPLES)

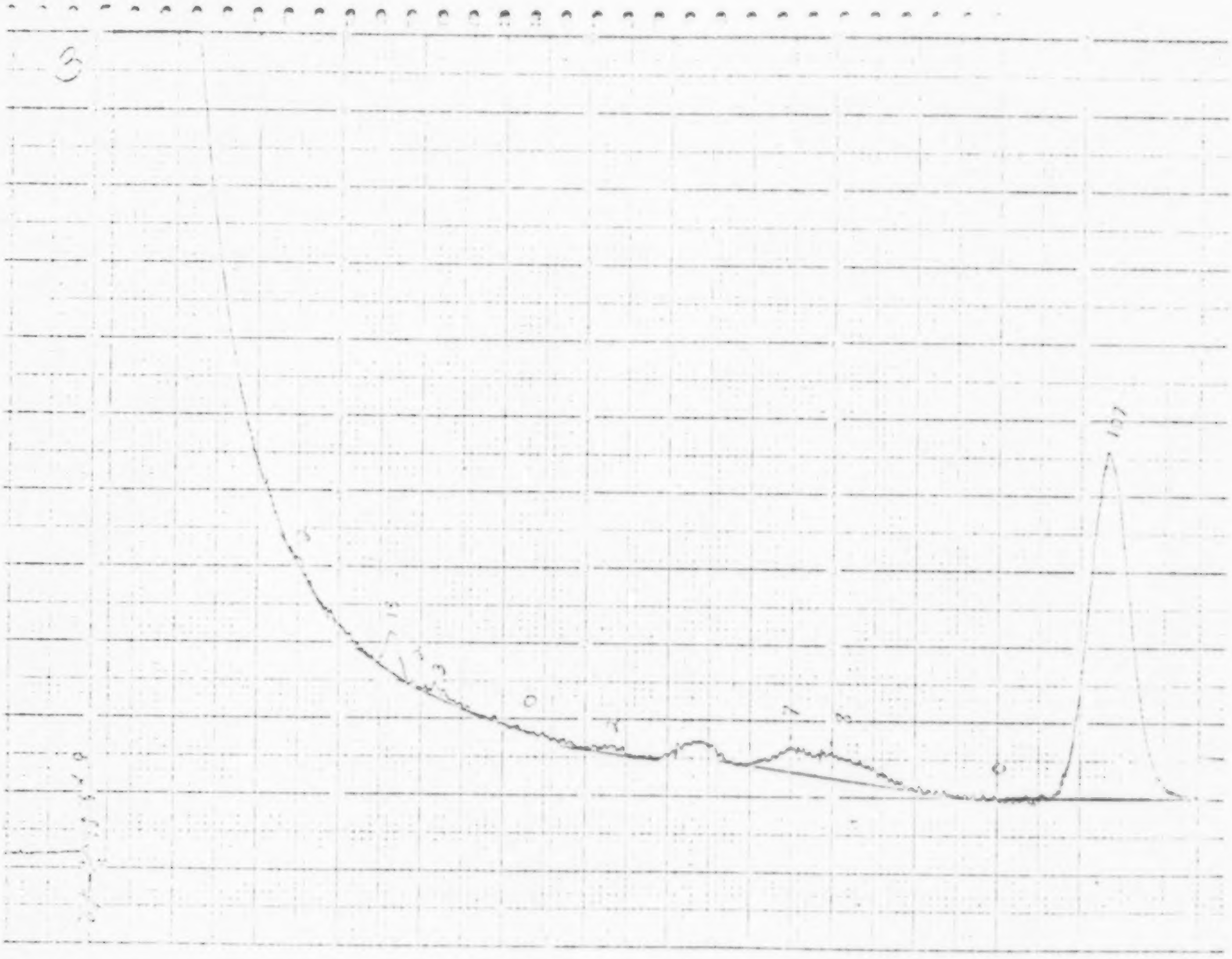


FIGURE A-11. UNUSED FLUOROPORE FILTER ANALYZED BY PHENOL DETECTION SYSTEM
(SECOND OF TWO SAMPLES)

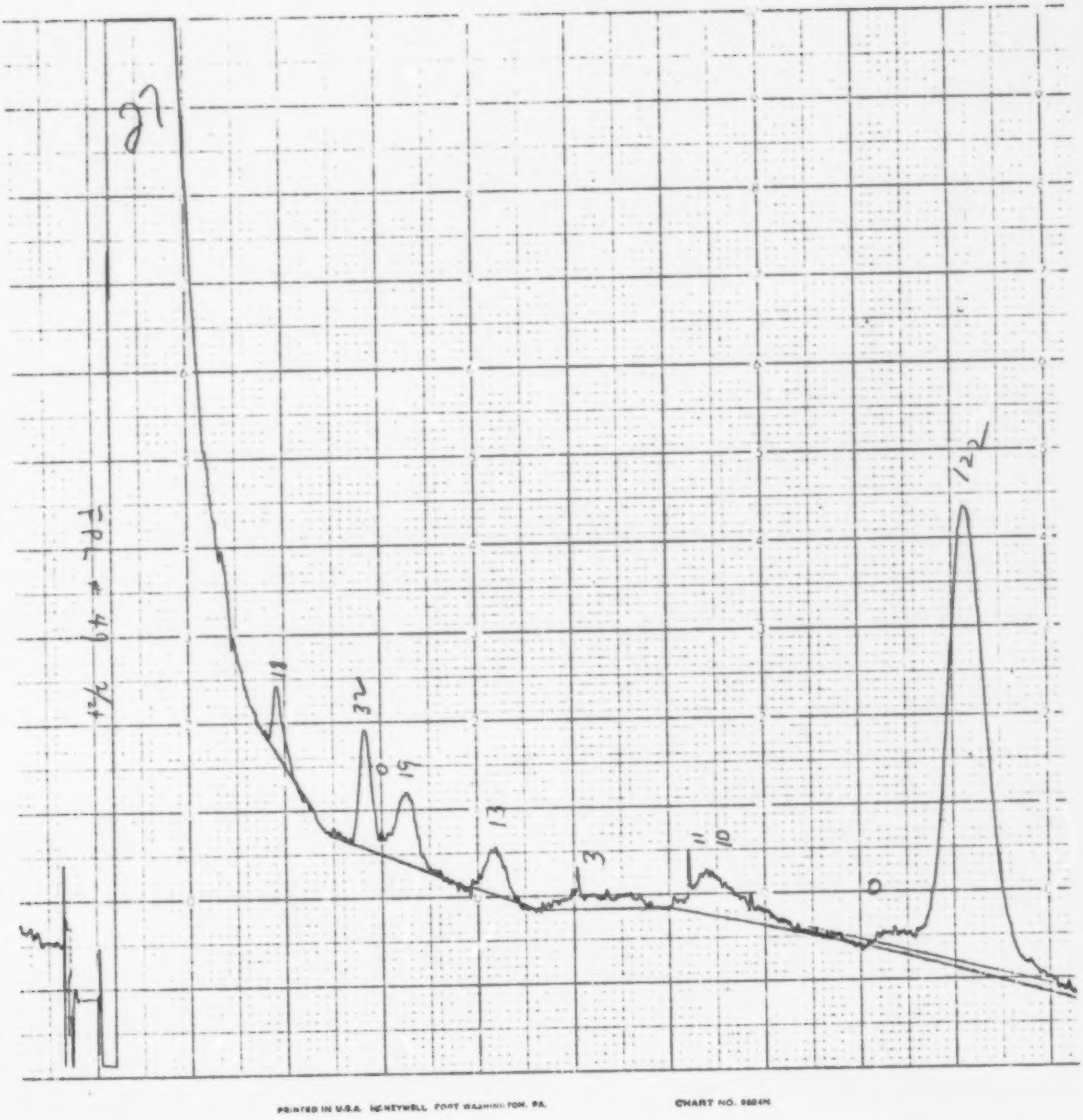


FIGURE A-12. DIESEL PARTICULATE SAMPLE ON FLUOROPORE FILTER ANALYZED BY PHENOL DETECTION SYSTEM

Diesel Emissions Analysis - Benzo-a-Pyrene

Interim Report - Engine #1

Introduction

Prior to undertaking the analysis of glass fiber filters containing deposits of diesel exhaust emissions for benzo-a-pyrene we reviewed four published methods of analysis.[1-4] Our choice was that of Sawicki *et al.*[1] as being the best suited for use in our laboratory. During the period of analysis we found that Sawicki had since changed his method for extraction of organic solubles from his original paper.[5] A critical comparison of the old and new methods was then made including a comparison of precision and accuracy of both methods. The nuclear magnetic resonance (proton) and infrared spectra of the extracted materials were also obtained.

Procedure

The method of Sawicki et al.[1] was chosen as that most adaptable to our laboratory methods. All or a known portion of the filters submitted for analysis was carefully placed in a Soxhlet extraction thimble and inserted in the extraction apparatus. One hundred ml of methylene chloride was then placed in a 250 ml Erlenmeyer flask. Heat was applied via hotplate and refluxing was allowed to occur for four hours at the rate of about 20 cycles/hour. At the end of this time the extract was transferred to a preweighed evaporating dish and the methylene chloride driven off at low heat. When dry, the dish was re-weighed to determine the weight of extractable organic material. This material was then redissolved in 5 ml of methylene chloride. It was this stock solution that was used for the remainder of the analyses.

Ten μl of solution were placed on an alumina thin layer plate (subsequently silica gel was also used) which was developed in a 19:1 pentane:ethyl ether solution. Markers of BaP in high concentration were also spotted so that the position of the "unknown" spots could be readily identified under ultraviolet light. After development, each BaP spot was scraped and washed with 50-100 ml of ethyl ether to remove the BaP from the substrate. The ether was then driven off under vacuum and the residue taken up in 1 ml of sulfuric acid. Once the acid was added, the solution was analyzed immediately by fluorescence spectrophotometry. The excitation wavelength was 470 nm while emission was measured at 540 nm. The intensity of the emitted light was then compared to a standard curve made from known amounts of BaP.

Reproduced from best available copy.

Several questions arose on various portions of the above procedure, therefore, we decided to speak directly with Dr. Sawicki. Two points of significance were determined during this conversation. The first was that certain chlorinated compounds may suppress the fluorescence emission. The second was that an ultrasonic extraction technique developed by his laboratory[5] appeared to be much more efficient than the Soxhlet technique in removing soluble organic material from the filters. We, therefore, began a comparison program to evaluate the differences in the extraction methods. At the same time we undertook a second program to determine the precision and accuracy of each method. To do this, a single filter was divided equally into quarters which were in turn divided in quarters. This allowed duplicate analyses to be made of each quarter by each technique and each quarter could also be spiked with a known amount of BaP for recovery studies. The results of these analyses are shown in Table II.

After reviewing the data obtained by the above procedures it was decided, for the sake of continuity, to continue the Soxhlet method of extraction. Other procedural changes which will be continued through Engine #2 are finalized as follows:

1. Extract 1/2 filter (divided into 2 equal sections for duplicate analyses) using hexane for 4 hours in a Soxhlet extractor.

2. Remove the hexane, except for 1-2 cc and quantitatively transfer to a 20 ml pre-weighed screw cap vial with repeated hexane rinses. (This allows any glass fibers in the extract to be removed prior to analysis of the extract.)

3. Evaporate to dryness at low temperature (under N_2 flow if possible).

4. Re-weigh vials to determine the amount of organic material extracted.

5. Add exactly 5 ml of hexane to the extract and shake until all residue is dissolved.

6. Spot a thin layer plate (alumina or silica gel) with 20 μl of solution and develop with 19:1 hexane:ethyl ether.

7. Scrape the spots due to BaP and extract with 1 ml of hexane, quantitatively filter and evaporate to dryness.

8. Add 1 ml sulfuric acid to the dried residue and analyze immediately using fluorescence measurements excitation: 470 nm and emission: 540 nm.

9. Using the remainder of the 5 ml portion (§ 5.) again dry and then add 1 ml CCl_4 and shake until dissolved.

10. Use appropriate portions of this solution to determine IR and NMR absorptions.

11. Transfer solutions to tapered vials for return to sender and further analyses.

Results

The final data for Engine #1 is shown in Table I. Calculations were based on a composite of as many external standard curves as were prepared during the analysis of each batch of filters.

Table II and IIa show the results from our analysis of the precision and accuracy of the technique employed.

Figure I illustrates the composite standard curves obtained for each batch of filters received while Figure II and IIa illustrate fluorescence spectra of standards and filters.

Discussion

While performing the initial analyses according to the method of Sawicki[1] we found several features of the protocol that were subject to question. These were:

1. The solvent front would not travel more than about 8 cm on the TLC plate.

2. The volume of washings and the relatively large surface area required for completion of the extractions seemed to be a possible source of contamination and/or loss of BaP.

3. The application of a vacuum for removal of the ether may cause sublimation of the BaP. There is also occasional contamination from ether extraction of the stopper in the flask.

4. The volatility of the methylene chloride is such that pipetting is made difficult.

5. The completeness of the Soxhlet technique on the filters is not fully described.

We, therefore attempted several changes in protocol. Initially, we changed extraction solvent from methylene chloride to carbon tetrachloride, a less volatile solvent, to make pipetting easier. However, we found that the fluorescence emission was suppressed. We also attempted transfers in a cold room to decrease volatility. Prior to attempting further changes in protocol we contacted Dr. Sawicki for his comments and advice. At this time we learned that chlorinated compounds suppress the fluorescence of BaP, that Dr. Sawicki is currently promoting ultrasonic extraction for removal of organic materials from glass fiber filters, and that silica gel could be used in place of alumina for TLC.

Changing the TLC substrate to silica gel and the eluting agent from pentane to hexane permitted the solvent front to move the full length of the plate thus allowing the BaP spot to fully develop rather than remain in the solvent front as before. The use of hexane as a solvent allowed the removal of all chlorinated compounds from the system and thereby any possible suppression of the fluorescence. Also, continuous shaking in a small volume of solvent and subsequent filtering of the substrate allows the BaP to be isolated without the use of large surface areas or vacuum. All of the above factors were considered with the purpose of reducing surface areas and solvent volumes to minimize the chances of contamination and/or loss of the BaP sample.

It has been decided to continue with the Soxhlet extraction technique for two reasons. The ultrasonic technique is highly abrasive in that ground glass is used to shred the filters and we feel that the apparent increased recovery of solubles may be due to factors other than normal chemical processes thereby changing the standard definition of "soluble". The other reason is that we have not found the precision of recovery to be any better for the ultrasonic than for the Soxhlet method. In fact the most recent recovery (for an Engine #2 filter and not shown here) has a coefficient of variation of 4% on extractables from 4 separate quadrants (quadruplicate analysis) using the Soxhlet method.

All filters have not been as uniform in their coatings as the one just mentioned, however. Through handling and storage notable variation in particulate density have been noted in several filters. This too may be one of the possible causes of generally poor precision in the overall analytical scheme.

High pressure liquid chromatography was briefly investigated as a possible alternative to the above analytical sequence. Although this technique may be promising we had difficulty in both separation of BaP from co-elutors and a too high detection limit. Since our time was limited we did not pursue this method any further.

The decreasing slopes of the standard curves over the several months of these tests has caused us concern. The reason for this change became obvious as the fluorescence spectrophotometer we were using had a complete breakdown just prior to the writing of this report. The circuit balance (dark current adjust) has been steadily drifting since the start of this project. Upon completion of repairs we expect that the gain and thus sample peak heights will return to those obtained initially.

It should be pointed out, however, that standard curves were run with each batch of filters. Therefore, the data obtained, even though the instrument characteristics varied, is consistent between batches.

Conclusions

The data reported is reproducible to better than ± 50%, and generally better than 10% for the BaP determinations using the Soxhlet technique. However, there are many factors, some of which have been corrected, that contribute to overall variations in the analysis. The most important of these are the amount of glassware used and the occasional irregularity in the particulate material deposited on the glass fiber filter. Recovery experiments at this time show poor (10-50%) accuracy. It is felt, however, that a misinterpretation has been made and that further study is necessary.

Future Work

During the week of February 24 the DuPont GC - mass spectrometer system 21-490B being housed at the Foundation will go on line. As soon as possible thereafter we plan to use the chemical ionization system to monitor our organic extracts. If, as we hope good separation and sensitivity is obtained we will quantitate the BaP in organic extracts using this system. This will eliminate almost totally the need for multiple transfers of extract solution and bring to a minimum the chance of BaP loss or sample contamination.

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DIESEL EMISSIONS STUDY

Table I

Benzo(a)Pyrene Analysis

Fuel	Condition	Sample No.	Filter No.	Particulate Weight (g)	Extract Weight (g)	Wt. % Extract in Particulates	Total BaP (μg)	Wt. % BaP in Particulates	Wt. % BaP in Extract	Sample Batch No.
		X	AR- 7	0.2605	0.1508	57.9	1.8	.0007	.0012	1
		X	AR-30	0.2171	0.1363	62.8	0.5	.0002	.0004	1
B	2100-100%	GS-1	AR-36	0.2037	0.1051	51.6	13.5	.0066	.0128	1
B	1600-50%	GS-2	AR-43	0.2319	0.1165	50.2	14.2	.0061	.0122	1
B	Idle	GS-3	AR-46	0.1425	0.0413	29.0	2.4	.0017	.0058	1
B	Composite	GS-4	AR-54	0.1106	0.0487	44.0	13.9	.0126	.0285	1
C	Composite	GS-5	AR-73	0.0979	0.0587	60.0	4.7	.0048	.0080	2
C	Idle	GS-6	AR-77	0.0759	0.0315	41.5	2.5	.0033	.0079	2
C	1600-50%	GS-7	AR-79	0.2043	0.1459	71.4	8.4	.0041	.0058	2
A	Idle	GS-8	AR-92	0.0645	0.0234	36.3	2.7	.0042	.0115	2
A	1600-50%	GS-9	AR-93	0.1629	0.1170	71.8	4.5	.0028	.0038	2
A	Composite	GS-10	AR-94	0.1013	0.0632	62.4	2.8	.0028	.0044	2
B	Composite	GS-11	AR-56	0.1073	0.0621	57.9	19.8	.0184	.0319	3
B	Composite	GS-12	AR-57	0.1148	0.0652	56.8	20.2	.0176	.0310	3
B	Idle	GS-13	AR-58	0.0501	0.0230	45.9	13.0	.0259	.0565	3
B	1600-0%	GS-14	AR-59	0.0704	0.0341	48.4	51.2	.0727	.1501	3
B	1200-100%	GS-15	AR-60	0.1797	0.0210	11.7	42.4	.0236	.2019	3
C	Composite	GS-16	AR-74	0.0989	0.0655	66.2	0.7	.0007	.0011	3
C	Composite	GS-17	AR-75	0.1025	0.0670	65.4	84.6	.0825	.1263	3
C	1600-0%	GS-18	AR-78	0.1224	0.0789	64.5	36.5	.0298	.0463	3
C	1600-100%	GS-19	AR-80	0.1208	0.0385	31.9	13.0	.0108	.0338	3
C	2100-0%	GS-20	AR-81	0.0965	0.0549	56.9	77.7	.0805	.1415	3
C	2100-50%	GS-21	AR-82	0.1525	0.1162	76.2	40.4	.0265	.0348	3
C	2100-100%	GS-22	AR-83	0.1727	0.1163	67.3	1.2	.0007	.0010	3
C	Idle	GS-23	AR-84	0.0515	0.0236	45.8	43.4	.0843	.1839	3
C	1600-50%	GS-24	AR-85	0.1809	0.0280	15.5	30.6	.0169	.1093	3
C	1600-50%	GS-25	AR-86	0.1627	0.1149	70.6	4.2	.0026	.0037	3
A+	Idle	GS-26	AR-95	0.0569	0.0305	53.6	15.0	.0264	.0492	3
DII-2	1600-50%	GS-27	AR-96	0.1718	0.0323	18.8	37.5	.0218	.1161	3
DII-2	Composite	GS-28	AR-97	0.1425	0.0975	68.4	29.6	.0208	.0304	3
DII-2	Composite	GS-29	AR-98	0.0921	0.0654	71.0	4.0	.0043	.0061	3

Table I (Continued)

Fuel	Condition	Sample No.	Filter No.	Particulate Weight (g)	Extract Weight (g)	Wt. % Extract in Particulates	Total BaP (μg)	Wt. % BaP in Particulates	Wt. % BaP in Extract	Sample Batch No.
C	2100-50%	GS-30	AR-69	0.1384						4
C	1600-75%	GS-31	AR-88	0.2136		Used for high pressure liquid chromatographic analyses				4
C	2100-100%	GS-32	AR-72	0.1433						4
C	1600-75%	GS-33	AR-65	0.0967	0.04644*	47.5	17.5	.0181	.0377	5
C	2100-25%	GS-34	AR-68	0.0424	0.02352*	54.6	20.8	.0491	.0898	5
C	2100-75%	GS-35	AR-71	0.1493	0.10839*	72.6	28.0	.0188	.0258	5
C	Idle	GS-36	AR-76	0.0319	0.01735*	54.3	38.5	.1207	.2219	5
B+	Composite	GS-37	AR-106	0.1758	0.05208	29.6	19.1	.0109	.0367	5
B+	Composite	GS-38	AR-107	0.2153	0.04060	18.9	30.4	.0141	.0749	5
C+	Composite	GS-39	AR-121	0.1379	0.01316	9.5	22.2	.0161	.1687	5
C+	Composite	GS-40	AR-122	0.1435	0.02791	19.4	14.8	.0103	.0530	5
B	Composite	GS-41	AR-130	0.1257	0.03956	31.5	7.6	.0060	.0192	5
B	Composite	GS-42	AR-133	0.1237	0.05392	43.6	4.6	.0037	.0085	5
A	1600-100%	GS-43	AR-143	0.1577	0.04892	31.0	19.9	.0126	.0407	5
A	Composite	GS-44	AR-147	0.0825	0.03924	47.6	4.7	.0057	.0120	5

*Sum of extract weight from 3 quadrants x $\frac{4}{3}$ to obtain whole filter extract weight.

Table II

Comparison of BaP Analysis between Soxhlet and Ultrasonic Extraction Processes

Filter*	BaP Extracted (μg)	Wt. Solubles Wt. Extracted (g)	Wt. BaP Wt. Extract
65 A-1	3.35	0.01190	281.5
A-2	1.75	0.01382	126.6
B-1	2.06	0.05409	38.1
B-2	3.84	0.02488	154.2
68 A-1	3.55	0.00743	417.8
A-2	3.25	0.00433	750.6
B-1	2.71	0.01809	149.6
B-2	1.33	0.00989	134.8
71 A-1	3.45	0.02913	118.4
A-2	3.20	0.03036	105.4
B-1	2.26	0.04698	48.1
B-2	0.93	0.03425	28.6
76 A-1	2.85	0.00499	571.1
A-2	2.50	0.00601	416.0
B-1	1.86	0.02178	85.3
B-2	3.11	0.01641	189.4

Results reflect analysis normalized to 1/4 filter.

*A-Soxhlet
B-Ultrasonic

Table IIa

Precision of Duplicate Analyses

Filter No.		BaP (1/4 filter) Mean	BaP (1/4 filter) Precision (%)	Extractables (1/4 filter) Mean	Extractables (1/4 filter) Precision (%)
Soxhlet	65	2.55	40.5	.01286	9.6
	68	3.40	5.7	.00588	34.0
	71	3.32	4.9	.02974	2.7
	76	2.67	8.4	.00549	12.0
Ultrasonic	65	2.95	38.9	.03948	47.7
	68	2.02	44.1	.01398	37.8
	71	1.60	53.8	.04061	20.2
	76	2.48	32.5	.01909	18.2

Accuracy of the Techniques

At this time values appear to be between 10 to 50% recovery. We feel that these estimates are in error, however, further review of the data is necessary.

Figure I

Linear Regression Data for Standard Curves

Batch No.	Number of Data Points	Correlation Coefficient	Intercept*	Slope**	Probability of Randomness
1	4	0.9987	-2.65	6860	<1:1000
2	23	0.9836	-4.39	5502	<1:1000
3	8	0.9978	+3.40	5546	<1:1000
4	4	0.9907	+4.00	3885	<1:1000
5	17	0.9244	-1.35	850	<1:1000

* Peak heights measured in mm.

** Variations due to change in instrumental parameters.

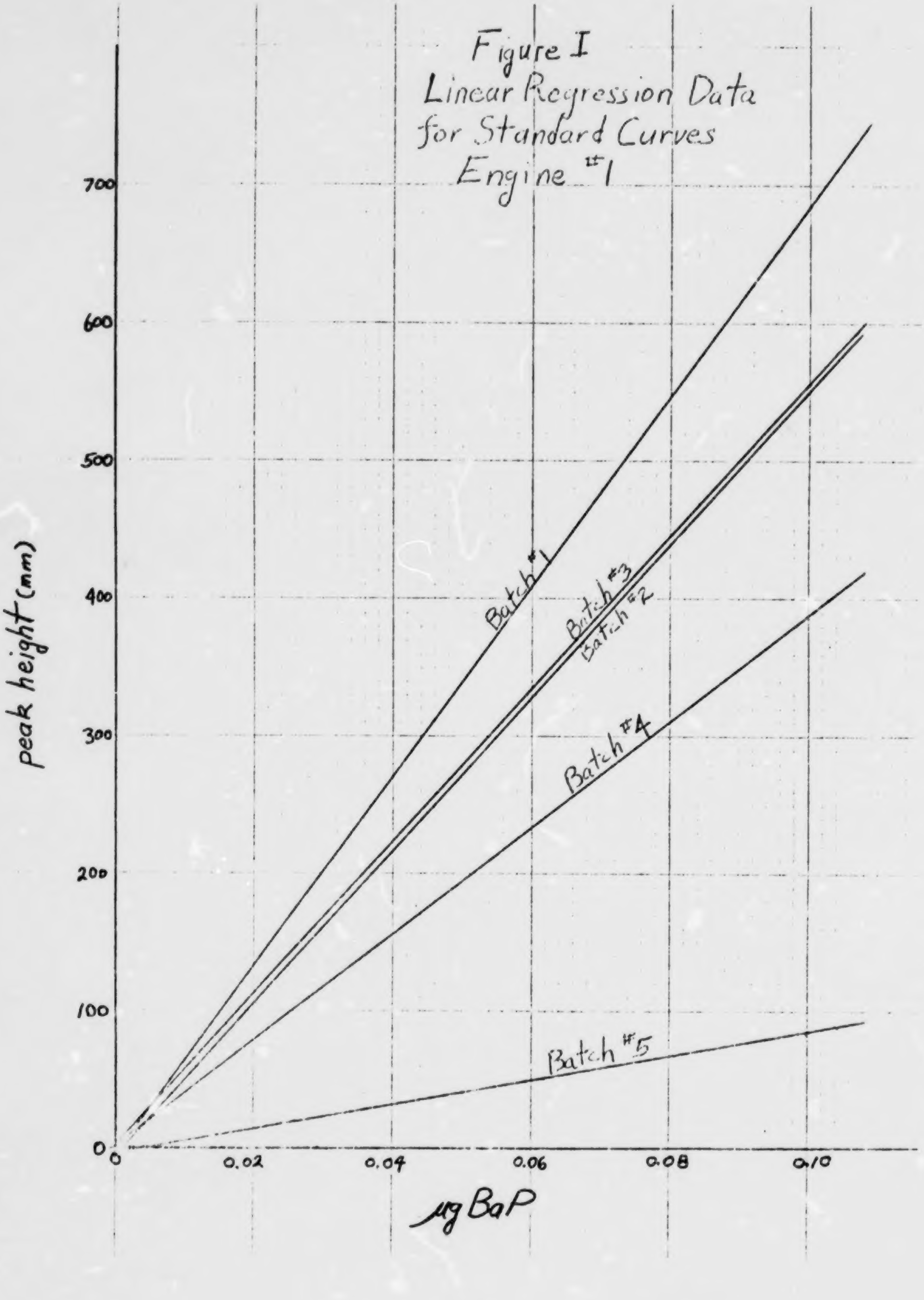
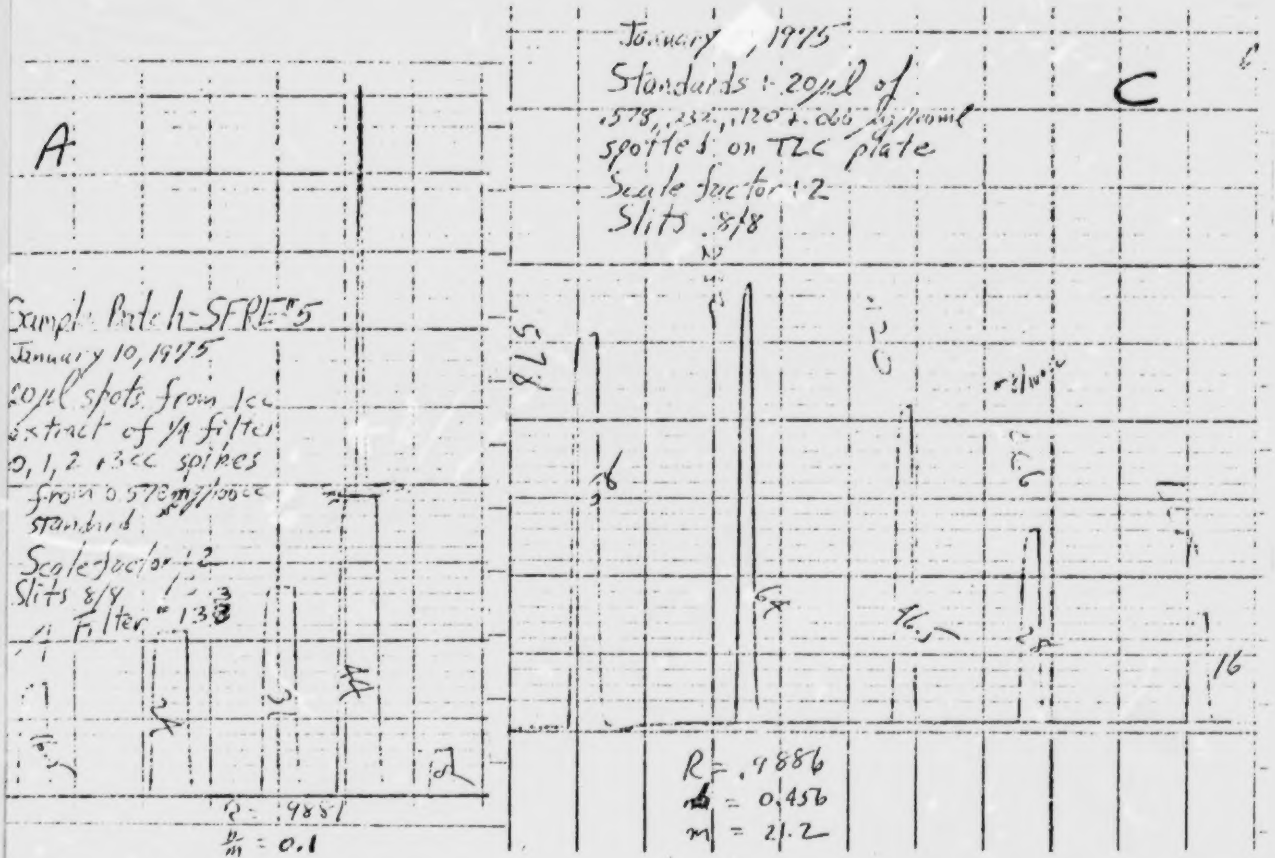


Figure I
Linear Regression Data
for Standard Curves
Engine #1
peak height (mm)
700
600
500
400
300
200
100
0
0
0.02
0.04
0.06
0.08
0.10
μg BaP
Batch #1
Batch #3
Batch #2
Batch #4
Batch #5

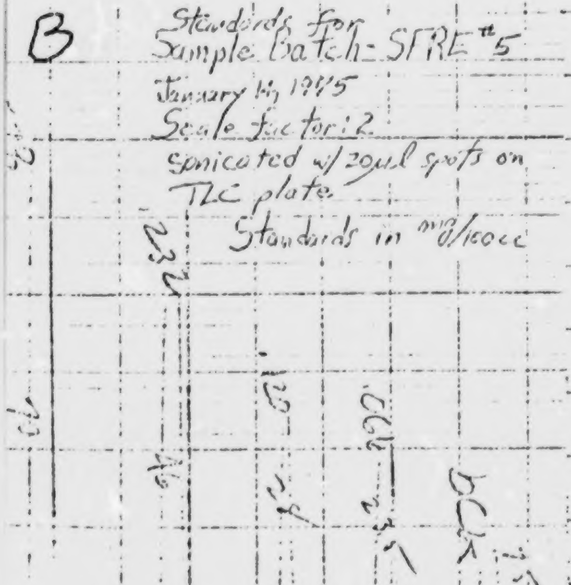


Sample Batch-SFRE #5
January 10, 1975
20µl spots from 1cc extract of 1/4 filter
0, 1, 2 + 3cc spikes from 0.578mg/100cc standard.
Scale factor: 2
Slits 8/8
Filter #133

R = .9851
b/m = 0.1

January , 1975
Standards: 20µl of .578, .232, .120 + .066 mg/100ml spotted on TLC plate
Scale factor: 2
Slits 8/8

R = .9886
b = 0.456
m = 21.2



Standards for Sample Batch-SFRE #5
January 14, 1975
Scale factor: 2
sonicated w/ 20µl spots on TLC plate
Standards in mg/100cc

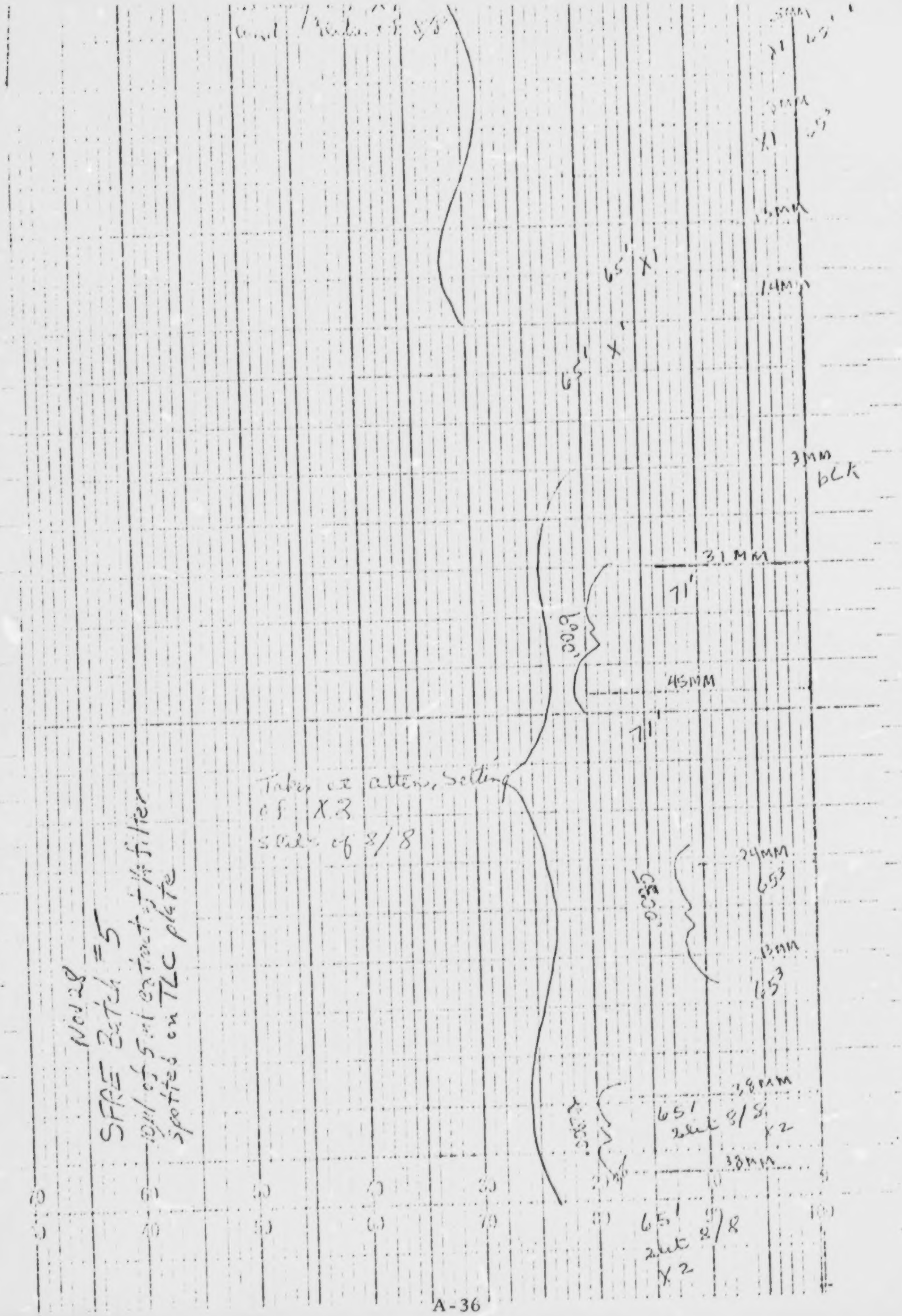
Figure II

Page from notebook - spectra taken during analysis of Batch #5.

A. Filter #133 - internal standards

B. External standards

C. External standards showing non-conforming peak which would normally be disregarded.



Nov 28
SFRE Batch #5
10μl of 5ml extract of # filter
spotted on TLC plate

Taken at atten. setting
of X2
scale of 8/8

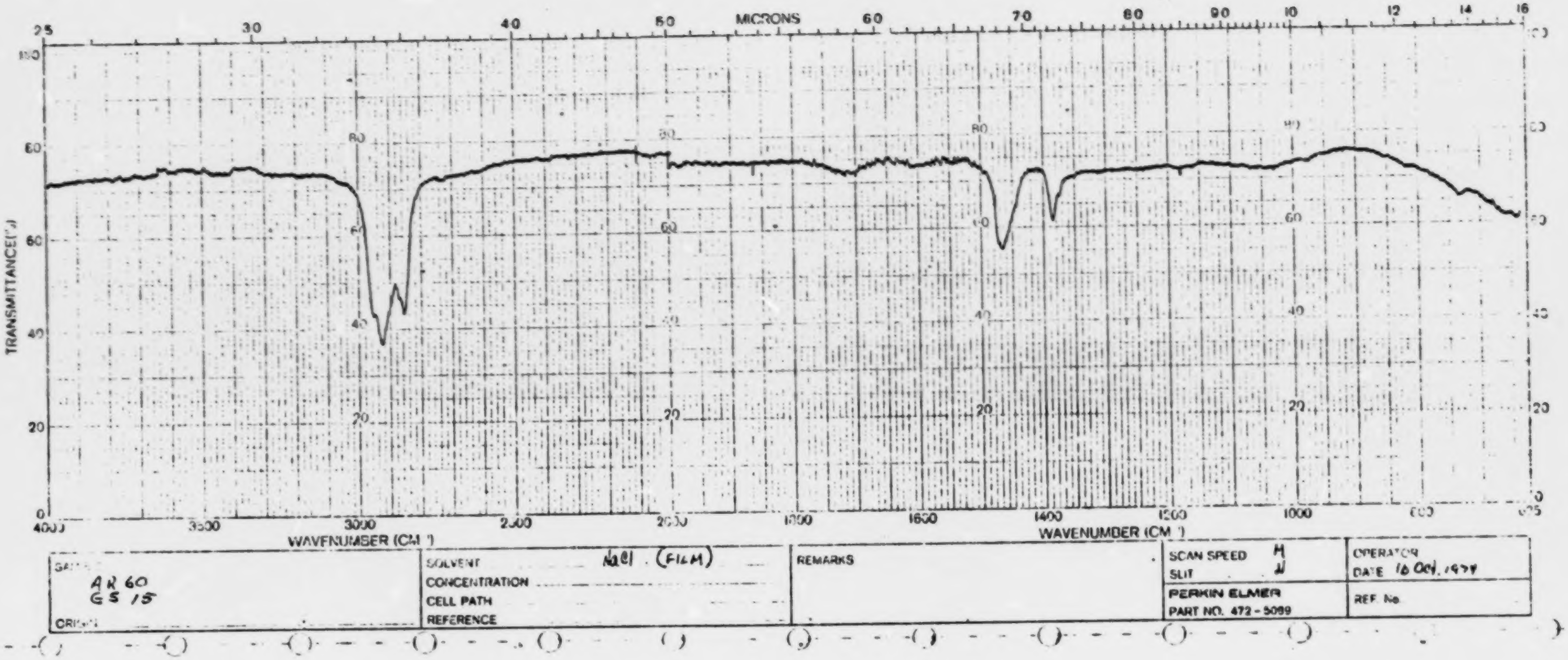


FIGURE A-13. INFRARED SPECTRUM OF ORGANIC SOLUBLE FRACTION OF A DIESEL PARTICULATE SMAPLE

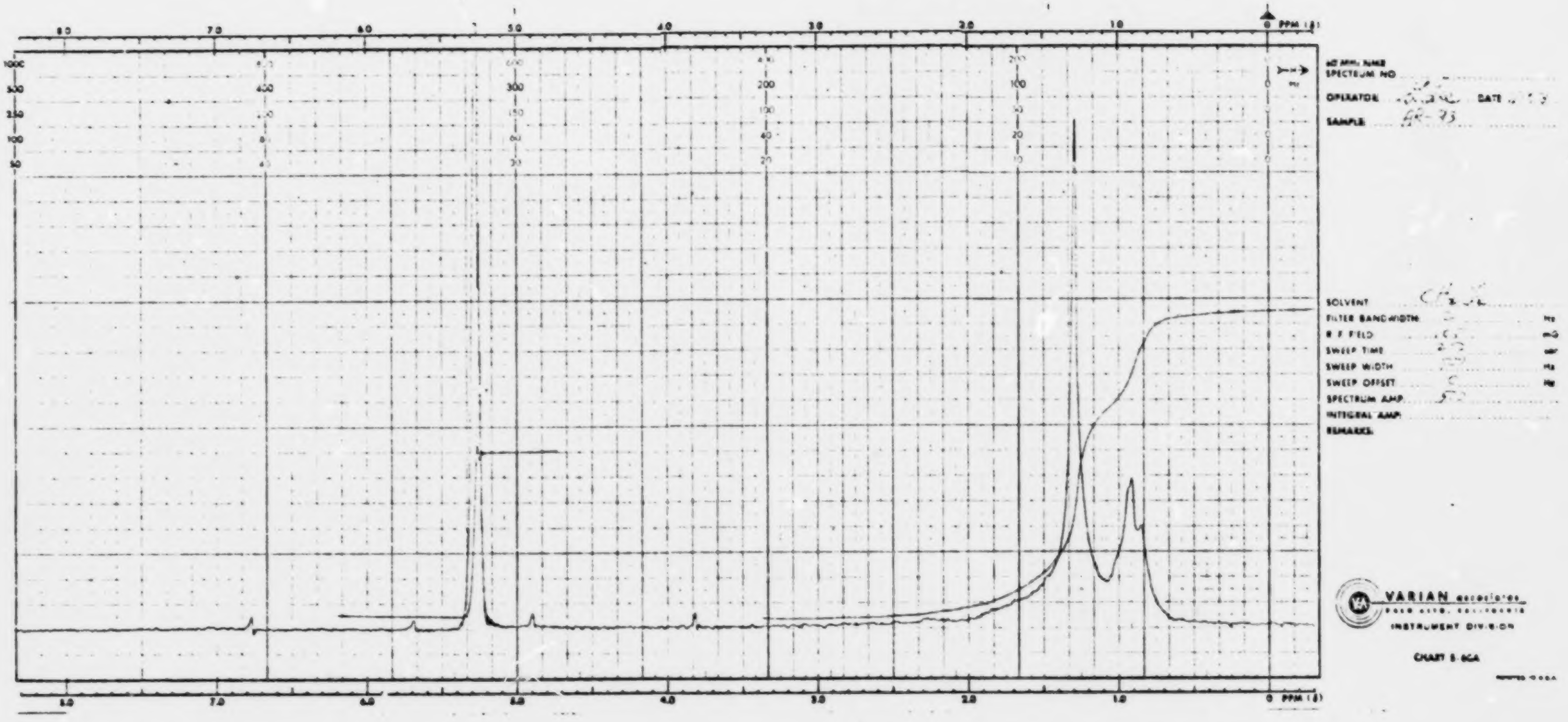


FIGURE A-14. NUCLEAR MAGNETIC RESONANCE SPECTRUM OF THE ORGANIC SOLUBLE FRACTION OF A DIESEL PARTICULATE SAMPLE

U.S. ARMY FUELS AND LUBRICANTS RESEARCH LABORATORY

Procedure for Saturates in Fuels

Scope

This method covers the determination of hydrocarbon saturates in samples having boiling points from 450°F to 1000°F.

Summary of Method

An accurate amount (0.03 to 0.1 g) of sample is diluted with a solvent containing 5% wt internal standard and analyzed by gas chromatography before and after saturate fraction isolation on an activated silica gel column. The amount and boiling point distribution of the hydrocarbons and the saturates in the sample are calculated.

Apparatus

Gas chromatograph equipped to meet conditions in Table I and apparatus for ASTM D1319-70.

Materials

1. Solvents: Pure n-hexane
   Pure cylohexane
   Pure 3-methylpentane
   Pure n-nonane
   Pure 4-methylnonane
   Pure n-decane
   Pure 2-methyldecane
   Pure n-undecane

2. Column: Dexsil 300
   Chromosorb P, AW, 45/60 mesh.

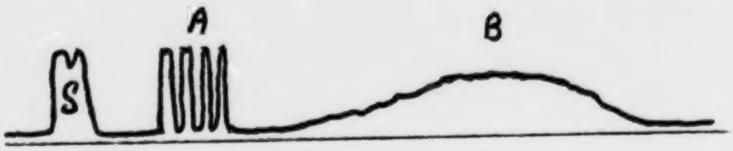
Procedure

In a weighted container containing a (0.03 to 0.1 g) amount of sample (Ws), add 0.6 g (0.8 ml) of solvent (60% wt cyclohexane, 17.5% wt n-hexane, 17.5% wt 3-methylpentane) containing a known percentage (5% wt) of internal standard (n-nonane, 4-methylnonane, n-decane, 2-methyldecane, n-undecane). Shake sample and analyze under conditions given in Table I for sample. Transfer 0.6-0.7 ml of diluted sample to column prepared for ASTM D1319 analysis (Standard Method of Test for Hydrocarbon Types in Liquid Petroleum Products by Fluorescent Indicator Adsorption). Column is prepared with 3/4 inch of glass hair in end. Allow 90% of saturate fraction to collect in 2 ml viel, cap, and analyze in same manner as for sample in Table I. Determine the boiling point distribution over the range 450-1000°F using simulated distillation software for the sample portion of the chromatogram. Calibration standard components are in Table 2.

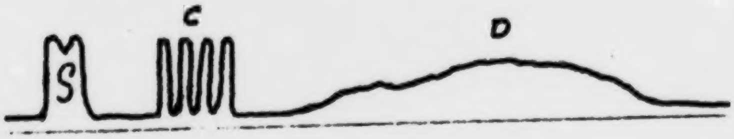
Calculations

Using the chromatogram areas defined below, calculate the amount of hydrocarbons and amount of saturates in the sample.

Chromatogram 1



Chromatogram 2



W_s = Weight of sample
W_{is} = Weight of Internal Standard
A = Area of Internal Standard from Chromatogram 1
B = Area of sample from Chromatogram 1
C = Area of Internal Standard from Chromatogram 2
D = Area of sample from Chromatogram 2
% Hyd = Percent hydrocarbons in sample
% Sat = Percent saturates in sample
S = Solvent

$$\% \text{ Hyd} = [(W_{is} \frac{B}{A})/(W_s)](100) \qquad (1)$$

$$\% \text{ Sat} = [(\% \text{ Hyd}) \frac{DK}{B}] \qquad (2)$$

Example: Saturate sample obtained from a diesel fuel

W_s = 0.0463 g
W_{is} = 0.03122 g
A = 27,232,804 mv-sec
B = 39,351,823 mv-sec
C = 31,678,205 mv-sec
D = 45,332,543 mv-sec

$$\% \text{ Hyd} = \frac{0.03122 \left(\frac{39341823}{27232804}\right) 100}{0.0463}$$

$$\% \text{ Hyd} = 97.4$$

$$K = \frac{27232804}{31678205} = 0.85967$$

$$\% \text{ Sat} = 97.45 \left(\frac{45332543}{39351823}\right) 0.85967$$

$$\% \text{ Sat} = 96.5$$

Note: This sample was obtained by HPLC and known to be approximately 99% pure saturaten from a diesel fuel.

TABLE 1

Gas Chromatograph Operating Conditions - Procedure for Saturates in Fuels

Gas Chromatograph

Column: Dual 4 ft x 1/8" O.D. (0.086" I.D.), 10% Dexsil 300 on chromasorb P, AW, 45/60 mesh

Detector: Dual Flame Ionization Detector 240 ml air, 40 ml hydrogen, 60 ml helium (column plus auxillary)

Temperatures:
Inlet: Water cooled septum inlet
Oven: 50°C to 390°C, 16°C/min, hold 4 min.
Detector: 400°C

Carrier Gas Flow Rate: 25 ml/min helium

Injection: 1µ on column

Integrator

	Calibration Standard*	Samples
Integrate	Automatic	ON
Output	Automatic peaks	12 sec intervals
Electrometer	256×10^{-9} AFS	256×10^{-10} AFS
Baseline Shift	ON, 50µV/peak	OFF
Digital Baseline Corrector	Auto, max rate	manual
Peak Corrector	Level	Level
Slope Sensitivity	10	10
Peak width/sec	10	10
Filtering	10	10
Area Reject	100	100
Teletype hard copy	ON	ON
Punched paper tape	ON	ON at 11 min.

TABLE 2

Calibration Standard - Procedure for Saturates in Fuels

n-saturate Component Carbon Number	v% (or weight)	Boiling Point	
		°C	°F
5	10.8	97	36
6	2.7	156	69
7	5.4	209	98
8	5.4	258	126
9	10.8	303	151
10	5.4	345	174
11	5.4	385	196
12	21.6	421	216
14	10.8	488	253
15	5.4	519	271
16	10.8	548	287
17	5.4	576	302
18	1.8g	602	317
20	1.8g	651	344
24	1.1g	736	391
28	0.7g	809	432
32	0.7g	874	468
36	0.7g	928	498
40	0.4g	977	525

Report

Report the percent and boiling point distribution of saturates and hydrocarbons in the sample.

Note: Precision and accuracy of this procedure are best in the BP range 450-900°F using an adequate sample size (minimal dilution) and a detector sensitivity of 10^{-9} AFS.

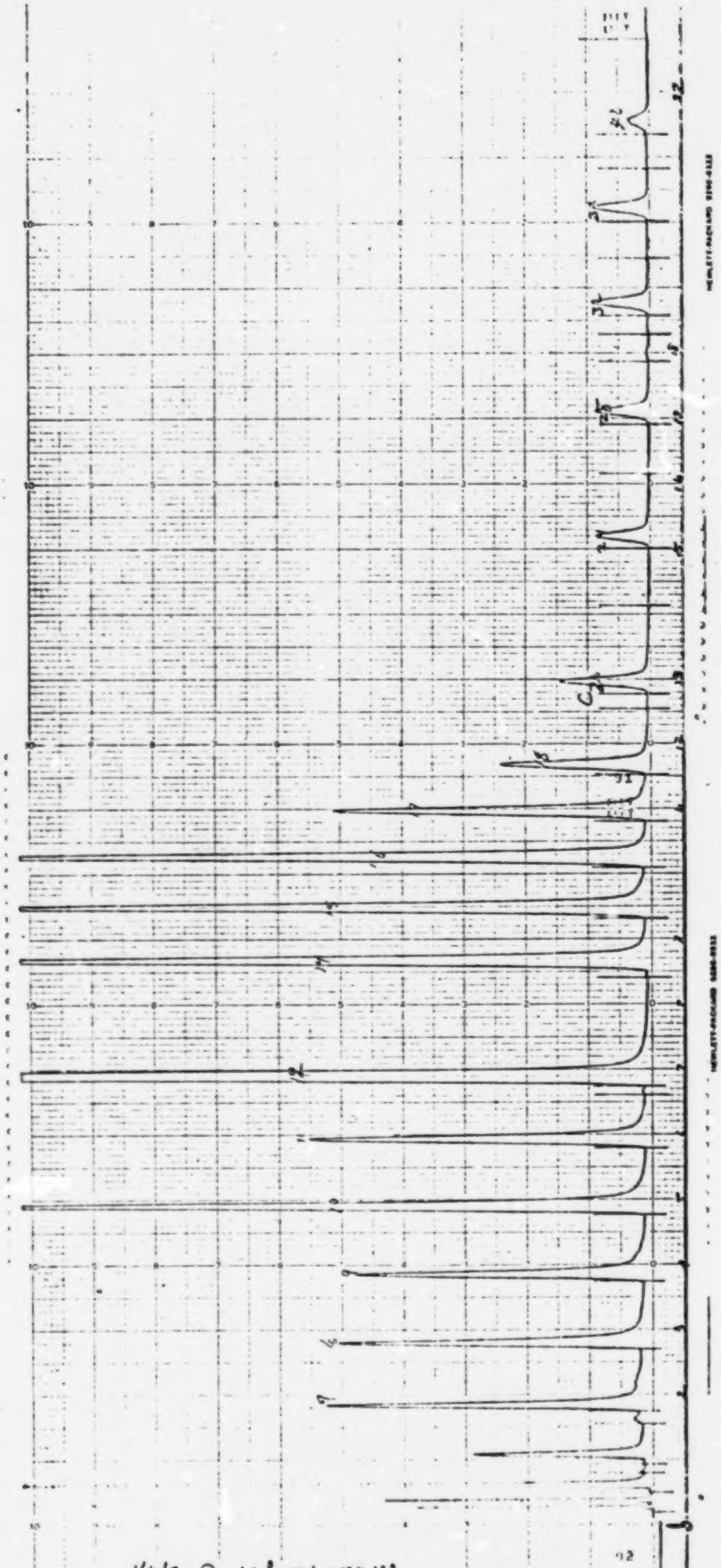


FIGURE A-15. SAMPLE STANDARD CALIBRATION OF DEXSIL COLUMN USED FOR PARAFFIN ANALYSIS

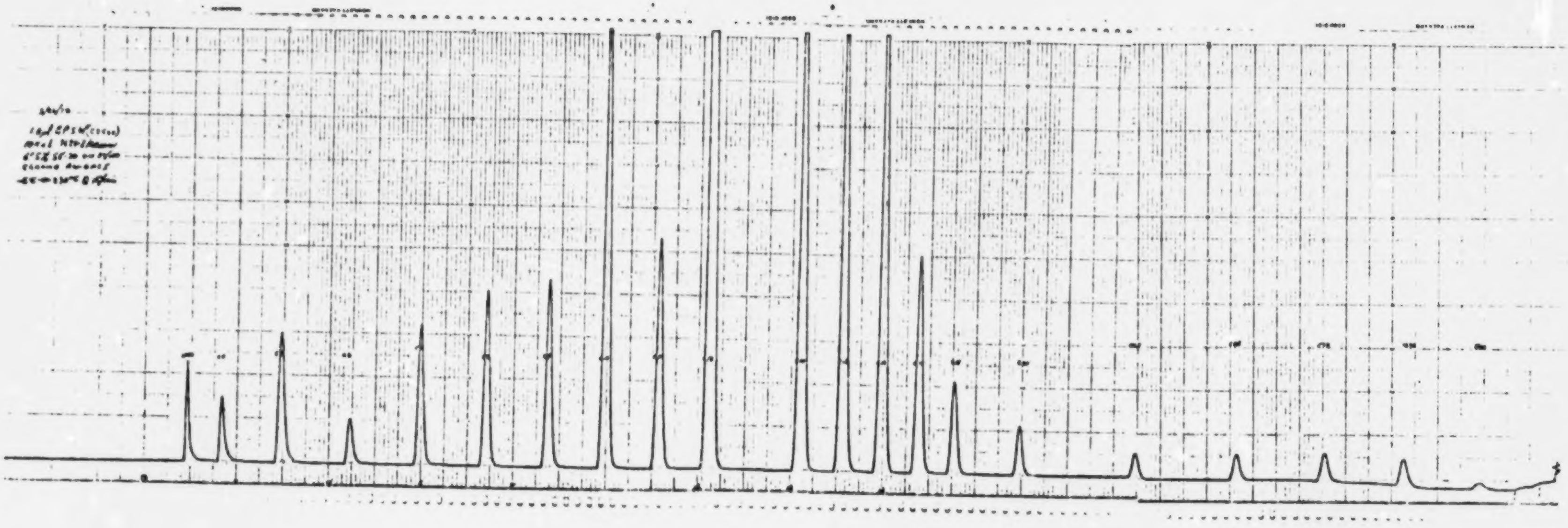


FIGURE A-16. SAMPLE STANDARD CALIBRATION OF SE-30 COLUMN USED FOR PARAFFIN ANALYSIS

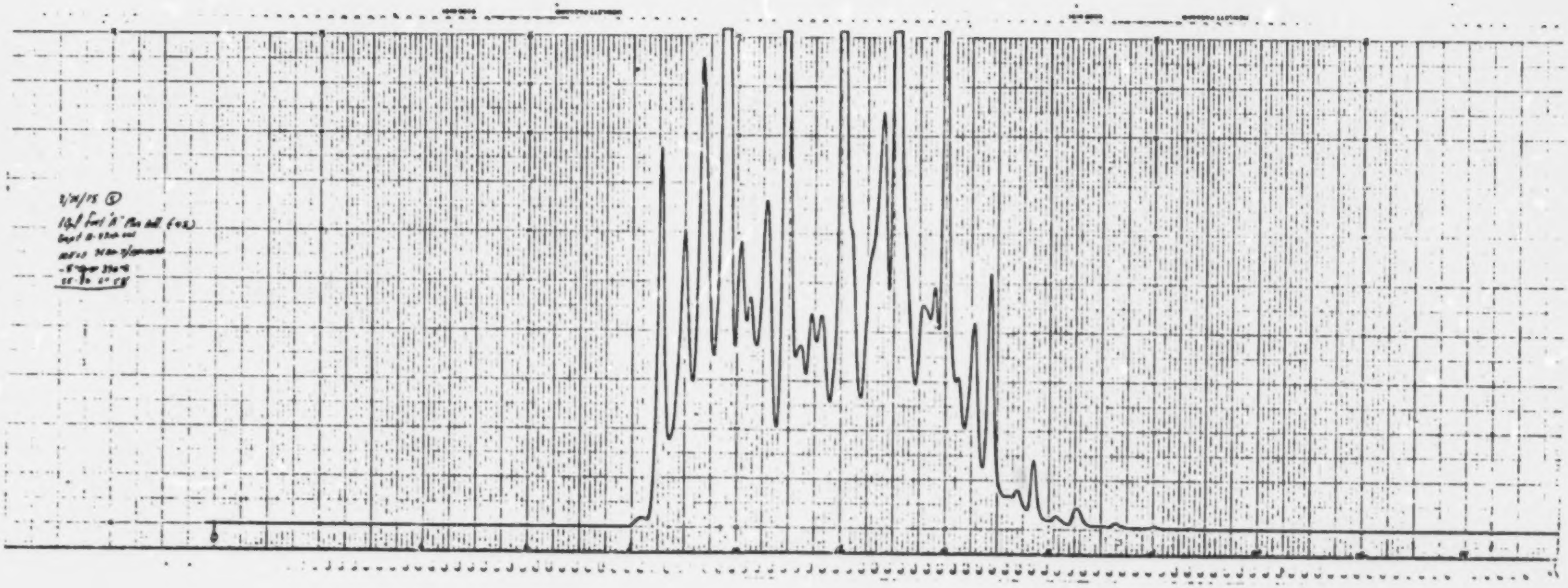


FIGURE A-17. ANALYSIS OF FUEL A ON SE-30 COLUMN

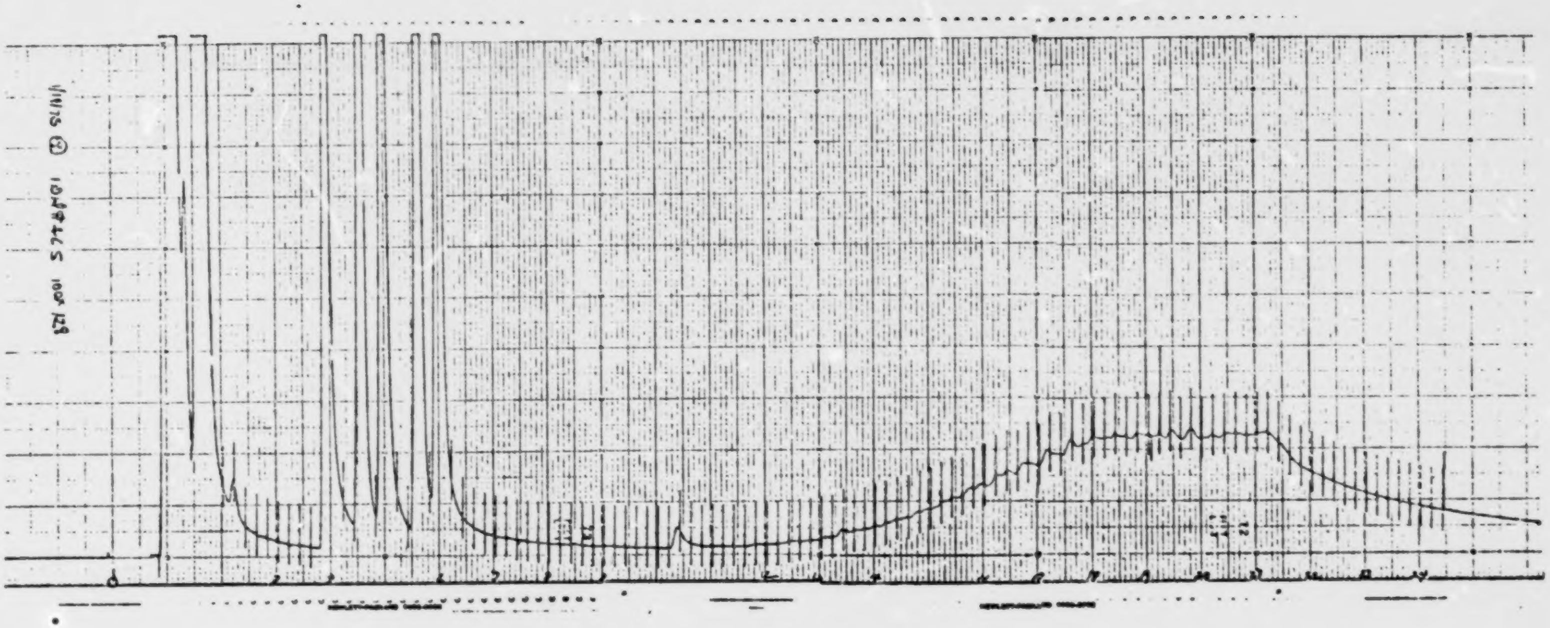


FIGURE A-18. ANALYSIS OF LUBRICATING OIL ON DEXSIL COLUMN

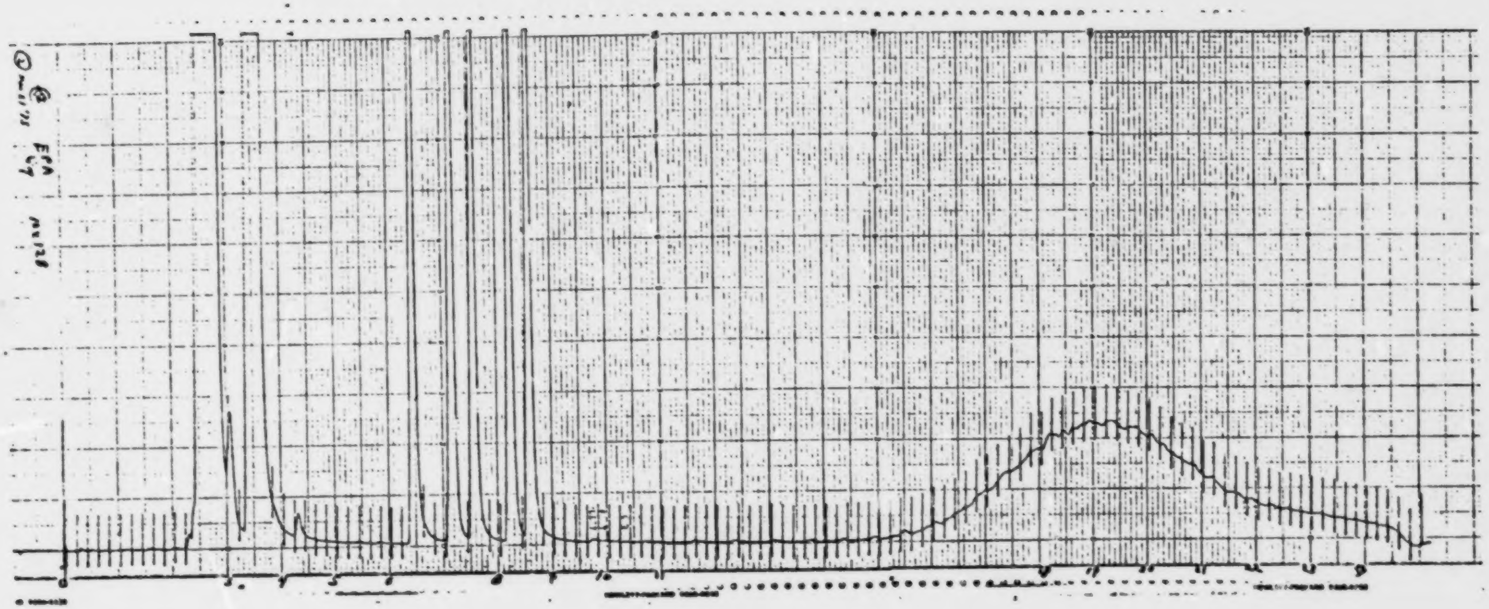


FIGURE A-19. ANALYSIS OF THE ORGANIC SOLUBLE FRACTION OF A TYPICAL DIESEL PARTICULATE SAMPLE FROM THE 6L-71T ENGINE

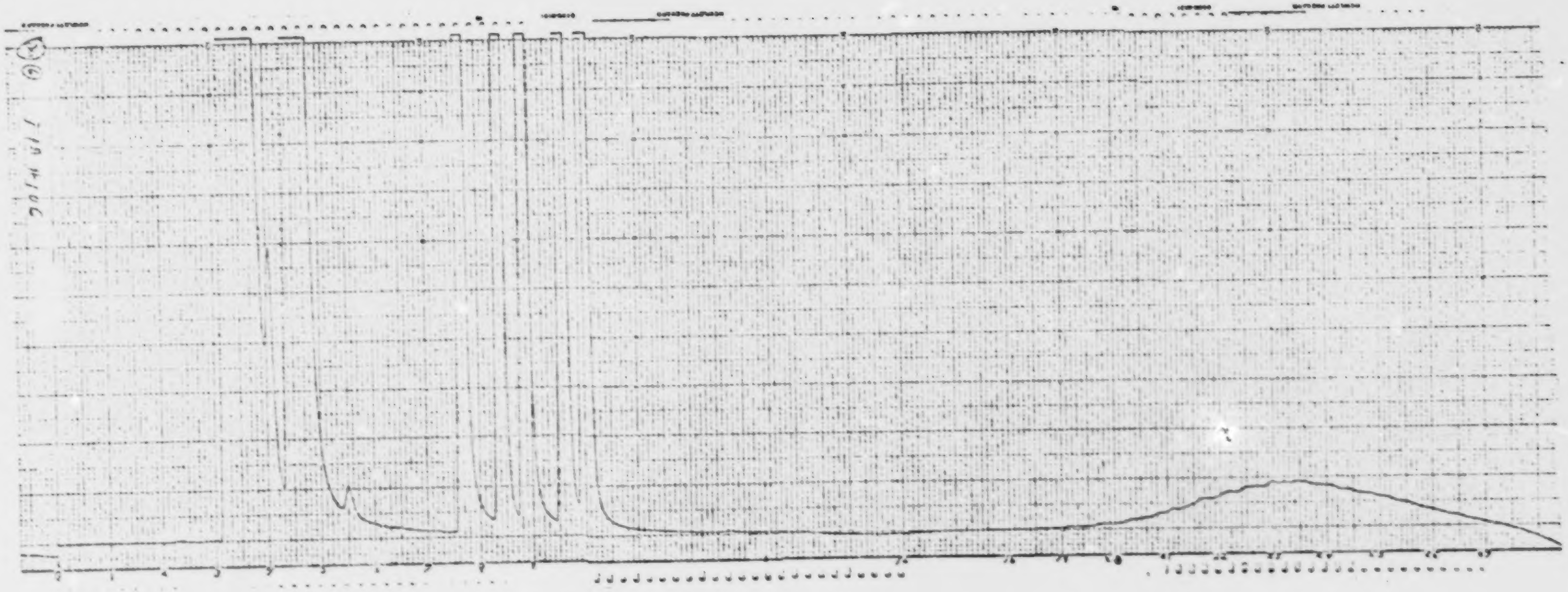


FIGURE A-20. ANALYSIS OF THE ORGANIC SOLUBLE FRACTION OF A TYPICAL DIESEL PARTICULATE SAMPLE FROM THE NTC-290 ENGINE

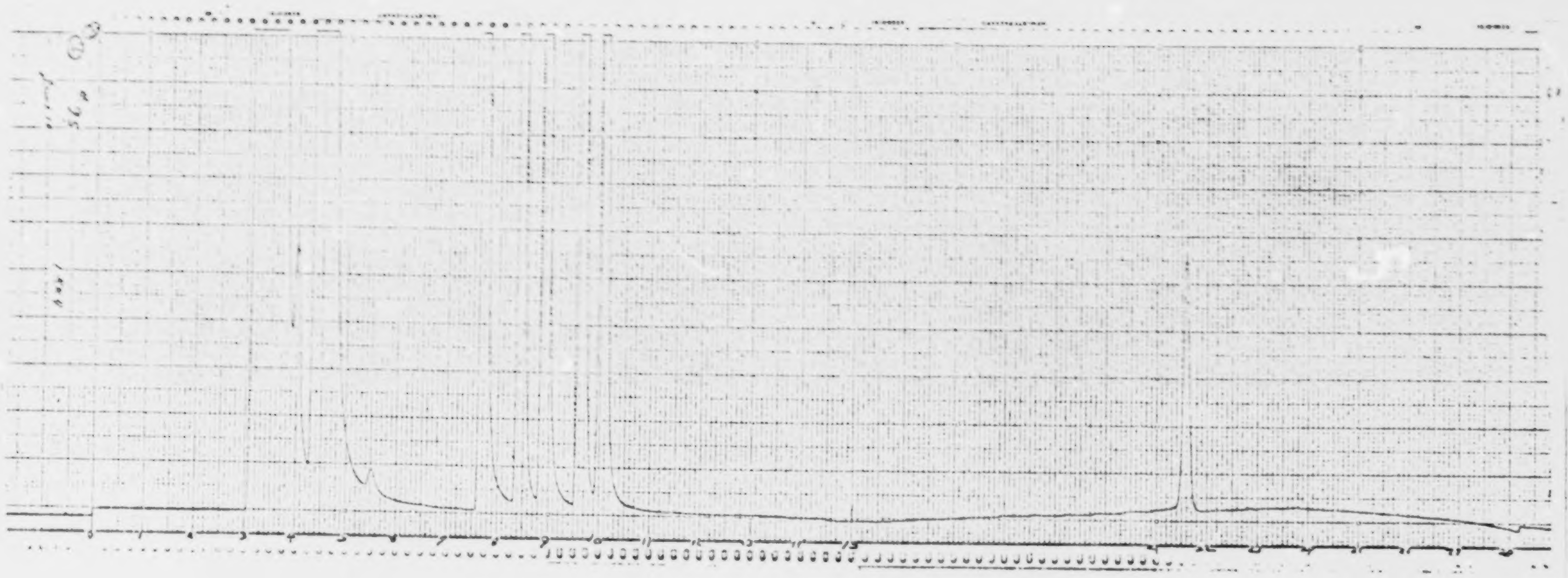
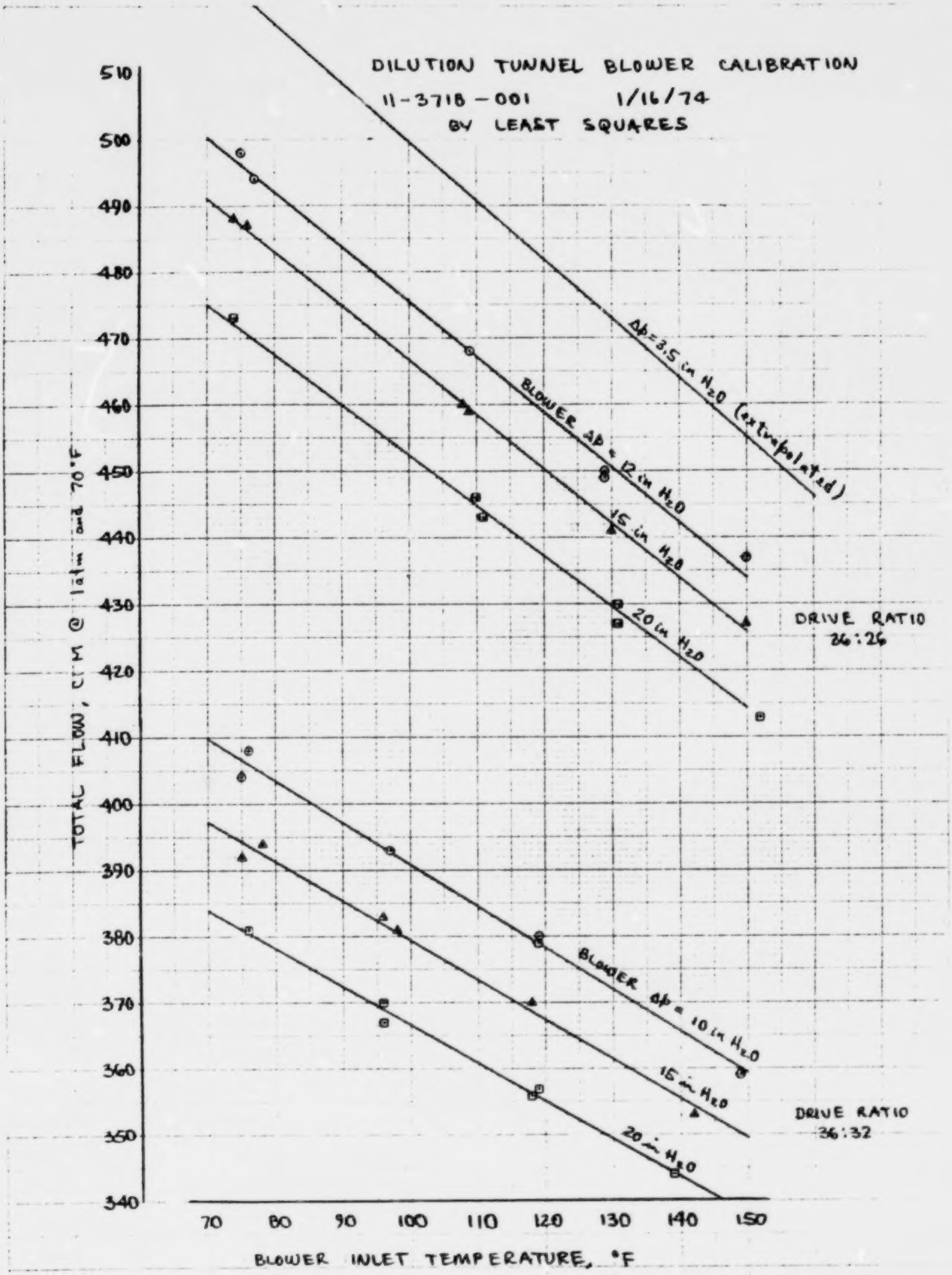


FIGURE A-21. ANALYSIS OF THE ORGANIC SOLUBLE FRACTION OF A DIESEL PARTICULATE SAMPLE FROM THE NTC-290 ENGINE SHOWING AN UNIDENTIFIED PEAK AT ABOUT 415°C

APPENDIX B

CALIBRATION AND CALCULATIONS ON TUNNEL AND SAMPLING DEVICES

DILUTION TUNNEL BLOWER CALIBRATION
11-3718-001 1/16/74
BY LEAST SQUARES
TOTAL FLOW, CFM @ 1atm and 70°F
BLOWER INLET TEMPERATURE, °F
510
500
490
480
470
460
450
440
430
420
410
400
390
380
370
360
350
340
70
80
90
100
110
120
130
140
150
Δp=3.5 in H₂O (extrapolated)
BLOWER Δp = 12 in H₂O
15 in H₂O
20 in H₂O
DRIVE RATIO 26:26
BLOWER Δp = 10 in H₂O
15 in H₂O
20 in H₂O
DRIVE RATIO 36:32

11-3718-001

DATE 1/16/74

MOTOR PULLEY 36 BLOWER PULLEY 26

CALCULATIONS - DILUTION TUNNEL BLOWER CALIBRATION

LOWER INLET TEMP., °F		BLOWER	BLOWER	LAMINAR FLOW ELEMENT				BLOWER
TARGET	ACTUAL	Δp, in H_2O	REV/min	Q, UNCORR.	P CORR.	T CORR.	Q, CORR.	V/R, ft^3/rev
75	75	12	1631	520.	0.9741	0.9834	498.	0.324
75	74	15	1628	509.	0.9746	0.9834	488.	0.317
75	74	20	1618	493.	0.9751	0.9834	473.	0.315
100	109	12	1634	548.	0.9746	0.8766	468.	0.322
100	109	15	1627	537.	0.9748	0.8766	459.	0.320
100	111	20	1620	523.	0.97[illegible]3	0.8686	443.	0.315
125	129	12	1634	563.	0.9748	0.8179	449.	0.320
125	130	15	1629	555.	0.9751	0.8155	441.	0.318
125	131	20	1621	540.	0.9756	0.8107	427.	0.314
150	150	12	1635	584.	0.9751	0.7675	437.	0.322
150	150	15	1629	574.	0.9753	0.7632	427.	0.319
150	152	20	1621	558.	0.9758	0.7589	413.	0.315
75	77	12	1631	517.	0.9746	0.9802	494.	0.322
75	76	15	1627	510.	0.9748	0.9802	487.	0.320
100	108	15	1627	538.	0.9751	0.8766	460.	0.320
100	110	20	1620	527.	0.9751	0.8686	446.	0.317
125	129	12	1633	564.	0.9748	0.8179	450.	0.321
125	131	20	1619	542.	0.9753	0.8131	430.	0.317

ATMOSPHERIC PRESSURE 29.44 in Hg

11-3718-001

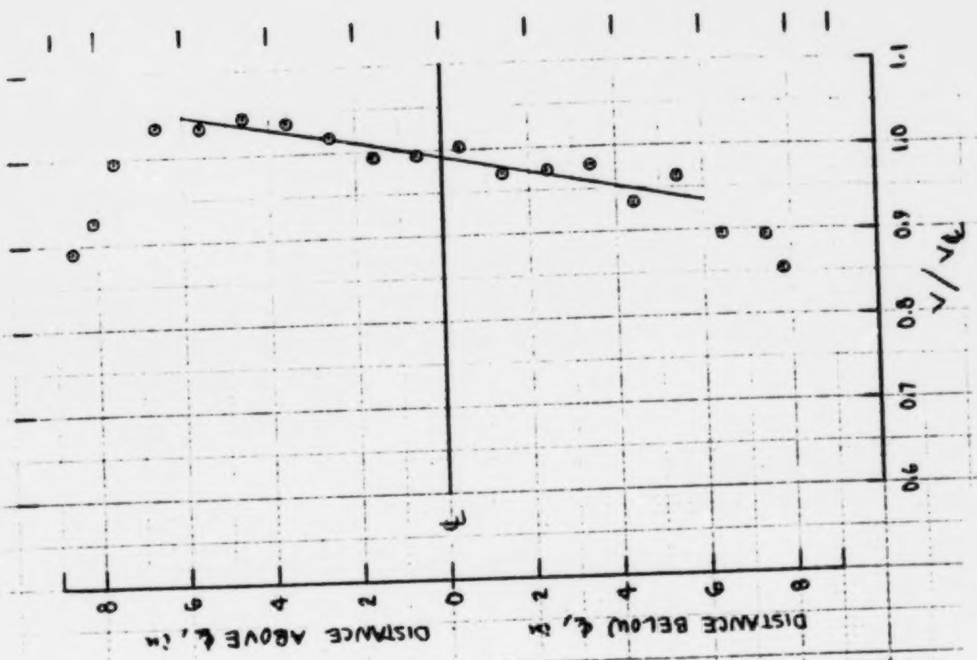
DATE 1/16/74

MOTOR PULLEY 36 BLOWER PULLEY 32

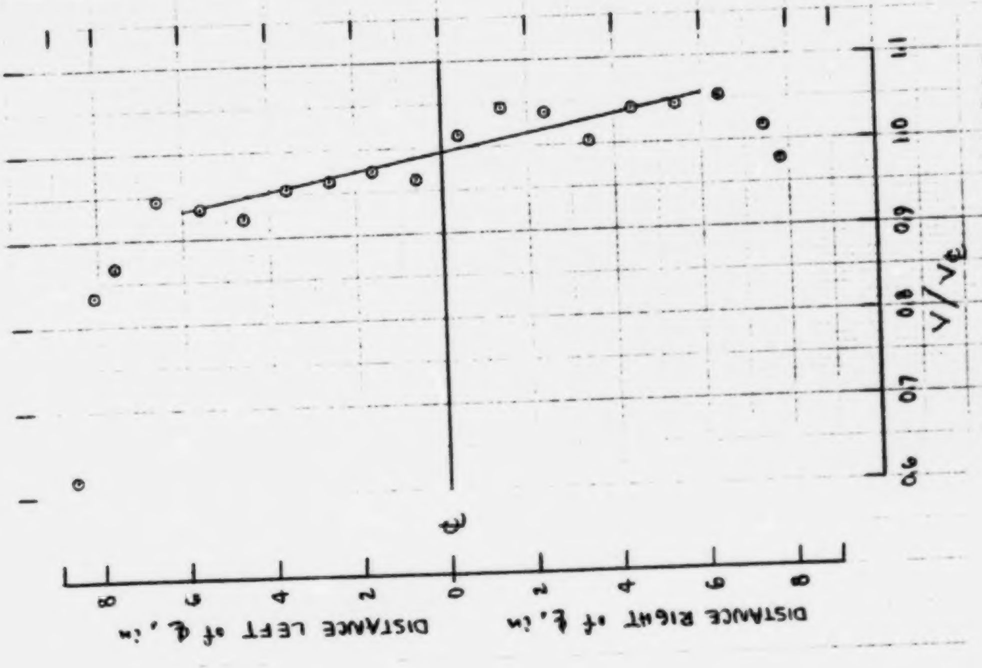
CALCULATIONS – DILUTION TUNNEL BLOWER CALIBRATION

BLOWER INLET TEMP., °F		BLOWER	BLOWER	LAMINAR FLOW ELEMENT			
TARGET	ACTUAL	Δp, in H_2O	REV/min	Q, UNCORR.	P CORR.	T CORR.	Q, CORR.
75	76	10	1334	426.	0.9764	0.9802	408.
75	78	15	1330	414.	0.9769	0.9737	394.
75	76	20	1325	398.	0.9771	0.9802	381.
100	97	10	1336	441.	0.9766	0.9129	393.
100	96	15	1332	428.	0.9769	0.9158	383.
100	96	20	1326	415.	0.9771	0.9129	370.
125	119	10	1337	458.	0.9766	0.8477	379.
125	118	15	1332	447.	0.9771	0.8477	370.
125	119	20	1328	432.	0.9776	0.8452	357.
150	149	10	1336	481.	0.9769	0.7632	359.
150	142	15	1332	457.	0.9771	0.7898	353.
150	139	20	1327	440.	0.9776	0.7990	344.
75	75	10	1336	419.	0.9766	0.9867	404.
75	75	15	1332	407.	0.9769	0.9567	392.
100	98	15	1331	427.	0.9769	0.9129	381.
100	96	20	1325	410.	0.9771	0.9158	367.
125	119	10	1335	459.	0.9769	0.8477	380.
125	118	20	1327	432.	0.9774	0.8426	356.

ATMOSPHERIC PRESSURE 29.42 in Hg



VERTICAL VELOCITY PROFILE
AT SAMPLING STATION



HORIZONTAL VELOCITY PROFILE
AT SAMPLING STATION

11-3718-001
2/12/74

VELOCITY PROFILE CALCULATIONS

VERTICAL PROFILE

inches above ℄	V, ft/sec		V/V℄		
	Run 1	Run 3	Run 1	Run 3	Avg.
8.6	5.4	9.5	0.867	0.915	0.891
8.1	5.55	10.0	0.891	0.963	0.927
7.6	6.1	10.5	0.979	1.012	0.996
6.6	6.3	11.0	1.011	1.060	1.036
5.6	6.4	10.8	1.027	1.040	1.034
4.6	6.5	—	1.043	—	1.043
3.6	6.5	10.7	1.043	1.031	1.037
2.6	6.35	—	1.019	—	1.019
1.6	6.2	10.3	0.995	0.992	0.994
0.6	6.2	—	0.995	—	0.995
-0.4	6.25	10.4	1.003	1.002	1.003
-1.4	6.05	—	0.971	—	0.971
-2.4	6.0	10.2	0.963	0.983	0.973
-3.4	6.1	—	0.979	—	0.979
-4.4	5.8	9.7	0.931	0.934	0.933
-5.4	6.0	—	0.963	—	0.963
-6.4	5.6	9.3	0.899	0.896	0.897
-7.4	5.55	9.3	0.891	0.896	0.893
-7.8	5.35	8.8	0.859	0.848	0.853
V℄	6.23	10.38			

HORIZONTAL PROFILE

inches left of ℄	V, ft/sec			V/V℄			
	Run 2	Run 4	Run 5	Run 2	Run 4	Run 5	Avg.
8.6	5.45	6.1	4.0	0.558	0.611	0.687	0.619
8.1	7.05	8.5	5.4	0.722	0.852	0.928	0.834
7.6	7.4	9.0	5.5	0.758	0.902	0.945	0.868
6.6	8.9	9.6	5.6	0.912	0.962	0.962	0.945
5.6	8.9	9.6	5.4	0.912	0.962	0.928	0.934
4.6	9.0	—	—	0.922	—	—	0.922
3.6	9.5	10.0	5.2	0.973	1.002	0.893	0.956
2.6	9.4	—	—	0.963	—	—	0.963
1.6	9.6	9.9	5.5	0.984	0.992	0.945	0.974
0.6	9.4	—	—	0.963	—	—	0.963
-0.4	10.0	10.0	5.9	1.025	1.002	1.014	1.014
-1.4	10.2	—	—	1.045	—	—	1.045
-2.4	10.3	10.3	6.0	1.055	1.032	1.031	1.039
-3.4	9.8	—	—	1.004	—	—	1.004
-4.4	10.5	10.3	5.9	1.076	1.032	1.014	1.041
-5.4	10.2	—	—	1.045	—	—	1.045
-6.4	10.4	10.4	6.1	1.066	1.042	1.048	1.052
-7.4	10.5	9.8	5.8	1.076	0.982	0.997	1.018
-7.8	10.0	10.0	5.3	1.025	1.002	0.911	0.979
	9.76	9.98	5.82				

- to get straight lines across duct center, use least squares on all points inside a 7-inch radius (14 for each profile)

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let $U = {}^{V}/V_{\text{℄}}$ $U = a + bx$

let x = distance from ℄, inches —— up and left are positive

$n = 14$ $a = \bar{U} - b\bar{x}$ $b = \dfrac{n\sum x_i U_i - \sum x_i \sum U_i}{n\sum x_i^2 - \left(\sum x_i\right)^2}$

VERTICAL PROFILE		HORIZONTAL PROFILE	
x	U	x	U
6.6	1.036	6.6	0.945
5.6	1.034	5.6	0.939
4.6	1.043	4.6	0.922
3.6	1.037	3.6	0.956
2.6	1.019	2.6	0.963
1.6	0.994	1.6	0.974
0.6	0.995	0.6	0.963
-0.4	1.003	-0.4	1.014
-1.4	0.971	-1.4	1.045
-2.4	0.973	-2.4	1.039
-3.4	0.979	-3.4	1.004
-4.4	0.933	-4.4	1.041
-5.4	0.963	-5.4	1.045
-6.4	0.897	-6.4	1.052

Vertical profile:

$\bar{x} = 0.10$

$\bar{U} = 0.9912$

$\sum x_i = 1.4$

$\sum U_i = 13.877$

$\sum x_i^2 = 227.64$

$\sum x_i U_i = 3.5252$

$b = 0.009396$

$a = 0.9903$

$\therefore U = 0.9903 + 0.009396\,x$

$U_{7.0} = 1.056$

= 0.925

Horizontal profile:

$\bar{x} = 0.10$

$\bar{U} = 0.9926$

$\sum x_i = 1.4$

$\sum U_i = 13.897$

$\sum x_i^2 = 227.64$

$\sum x_i U_i = -0.9418$

$b = -0.01025$

$a = 0.994$

$U = 0.994 - 0.01025\,x$

$U_{7.0} = 0.922$

$U_{-7.0} = 1.066$

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Integration of average velocity profiles (from summary of 2/12)

$$V_b = \frac{2}{R^2}\int_0^R V_r\,dr = \frac{2}{R^2}\sum_{i=1}^{N}(\overline{V_r})_i(\Delta r)_i$$

V_b (corrected avg) = 0.898 $V_{\mathfrak{t}}$

$\therefore V_{\mathfrak{t}}/V_b \simeq 1.114$ $\quad V_{max}/V_b \simeq 1.16$

TOP

r	V	V_r	$\overline{V_r}$	Δr	$\overline{V_r}\,\Delta r$
8.85	0	0	3.8313	0.25	0.9578
8.6	0.891	7.6626	7.5856	0.5	3.7928
8.1	0.927	7.5087	7.5392	0.5	3.7696
7.6	0.996	7.5696	7.2036	1.0	7.2036
6.6	1.036	6.8376	6.3140	1.0	6.3140
5.6	1.034	5.7904	5.2941	1.0	5.2941
4.6	1.043	4.7978	4.2655	1.0	4.2655
3.6	1.037	3.7332	3.1913	1.0	3.1913
2.6	1.019	2.6494	2.1199	1.0	2.1199
1.6	0.994	1.5904	1.0937	1.0	1.0937
0.6	0.995	0.597	0.2985	0.6	0.1791
0	1.000	0			
				Σ =	38.1814

V_b(top) = 0.9750

BOTTOM

r	V	V_r	$\overline{V_r}$	Δr	$\overline{V_r}\,\Delta r$
8.85	0	0	3.3267	1.05	3.4930
7.8	0.853	6.6534	6.6308	0.4	2.6523
7.4	0.893	6.6082	6.1745	1.0	6.1745
6.4	0.897	5.7408	5.1495	1.0	5.1495
5.4	0.963	5.2002	5.008	1.0	5.008
4.4	0.933	4.1052	3.7169	1.0	3.7169
3.4	0.979	3.3286	2.8319	1.0	2.8319
2.4	0.973	2.3352	1.8473	1.0	1.8473
1.4	0.971	1.3594	0.8803	1.0	0.8803
0.4	1.003	0.4012	0.2006	0.4	0.0802
0	1.000	0			
				Σ =	31.8338

V_b(bottom) = 0.8129

LEFT

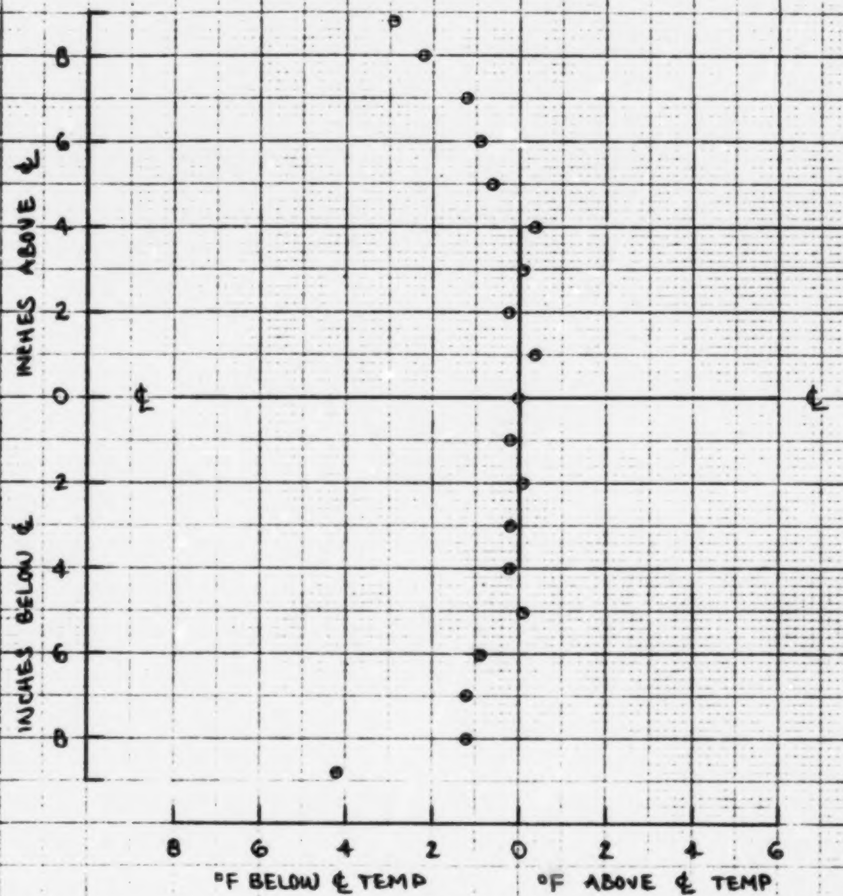
r	V	V_r	$\overline{V_r}$	Δr	$\overline{V_r}\,\Delta r$
8.85	0	0	2.6617	0.25	0.6654
8.6	0.619	5.3234	6.0394	0.5	3.0197
8.1	0.834	6.7554	6.6761	0.5	3.3380
7.6	0.868	6.5968	6.4169	1.0	6.4169
6.6	0.945	6.2370	5.7337	1.0	5.7337
5.6	0.934	5.2304	4.7358	1.0	4.7358
4.6	0.922	4.2412	3.8414	1.0	3.8414
3.6	0.956	3.4416	2.9727	1.0	2.9727
2.6	0.963	2.5038	2.0311	1.0	2.0311
1.6	0.974	1.5584	1.0681	1.0	1.0681
0.6	0.963	0.5778	0.2889	0.6	0.1733
0	0.983	0			
				Σ =	33.9962

V_b(left) = 0.8681 (0.8931 corrected)

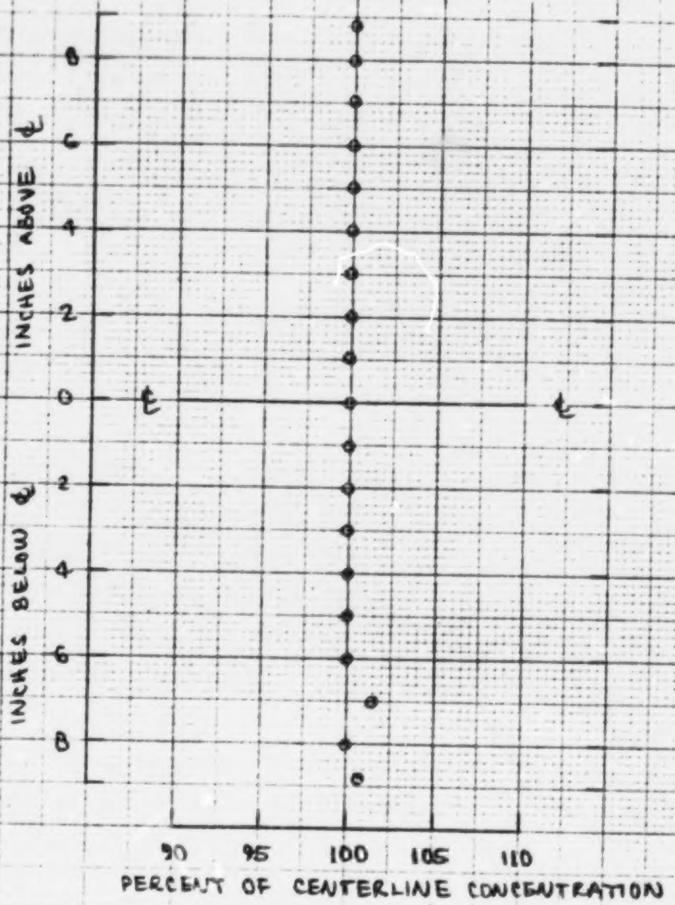
RIGHT

r	V	V_r	$\overline{V_r}$	Δr	$\overline{V_r}\,\Delta r$
8.85	0	0	3.8181	1.05	4.0090
7.8	0.979	7.6362	7.5847	0.4	3.0339
7.4	1.018	7.5332	7.1330	1.0	7.1330
6.4	1.052	6.7328	6.1879	1.0	6.1879
5.4	1.045	5.6430	5.0755	1.0	5.0755
4.4	1.041	4.5804	3.9970	1.0	3.9970
3.4	1.004	3.4136	2.9536	1.0	2.9536
2.4	1.039	2.4936	1.9783	1.0	1.9783
1.4	1.045	1.4630	0.9343	1.0	0.9343
0.4	1.014	0.4056	0.2028	0.4	0.0811
0	0.983	0			
				Σ =	35.3836

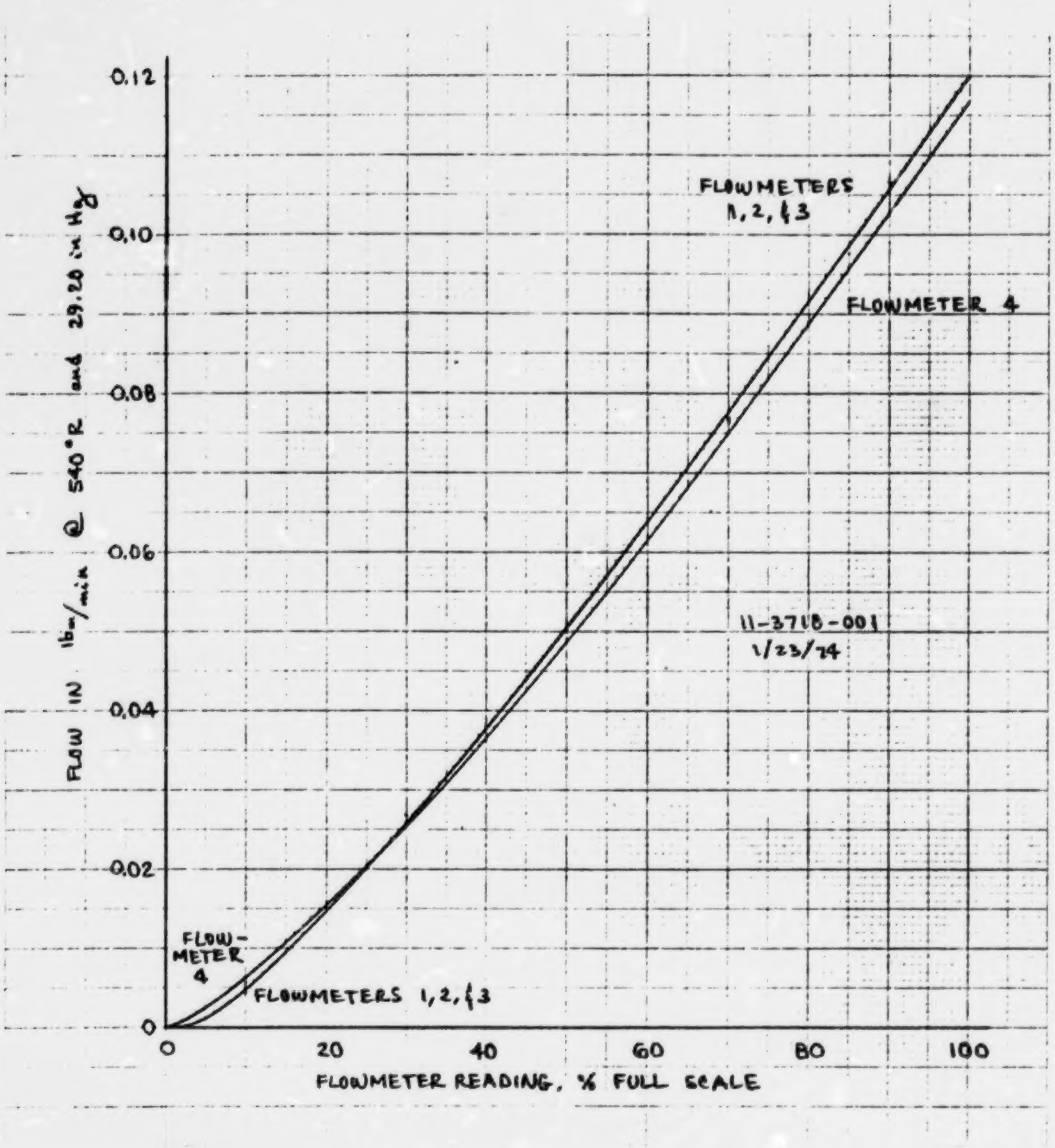
V_b(right) = 0.9035
(0.9191 corrected)



DILUTION TUNNEL TEMPERATURE PROFILE, AVERAGE OF THREE OPERATING CONDITIONS



DILUTION TUNNEL CONCENTRATION PROFILE USING GL-71T ENGINE AS GAS GENERATOR (VERTICAL)



0.12
0.10
0.08
0.06
0.04
0.02
0
FLOW IN lbm/min @ 540°R and 29.20 in Hg
0
20
40
60
80
100
FLOWMETER READING, % FULL SCALE
FLOWMETERS 1, 2, & 3
FLOWMETER 4
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FLOW-METER 4
FLOWMETERS 1, 2, & 3

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SAMPLING RATE DATA & CALCULATIONS

PROBE		TIP		
LOCATION	No.	I.D., in	AREA, in^2	AREA, ft^2
HI-VOL (8×10)	—	3.47 (derived)	9.46	0.0657
4×47 unit	1	0.500	0.196	0.00136
	2	0.500	0.196	0.00136
	3	0.501	0.197	0.00137
	4	0.501	0.197	0.00137
ERC sampler	2	0.2535	0.0505	0.000350
	3	0.2005	0.0316	0.000219
	4	0.3035	0.0723	0.000502
	5	0.1510	0.0179	0.000124
	6	0.1005	0.00793	0.0000551

TUNNEL CALIBRATION

$$V_{sb} = N \frac{\text{counts}}{\text{time}} \left(\frac{T_s}{T_E} \times \frac{P_E}{P_s} \right)$$

at blower Δp of 3.5 in H_2O

N = 11.9 for 4×47 system, 12.4 for HI-VOL system

ISOKINETIC SPEEDS

HI-VOL: $V_{iso} \doteq 1.11\, V_{sb} = \frac{Q_s\,(\text{sample})}{A_s\,(\text{sample})} = \frac{\dot{m}/\rho_s}{A_s\,(\text{sample})} = \frac{278.9\sqrt{\rho_{OR}\Delta P_{OR}}}{\rho_s A_s\,(\text{sample})}$ ft/hr

$= \frac{4.648\sqrt{\rho_{OR}\Delta P_{OR}}}{\rho_s A_s\,(\text{sample})} = \frac{70.76\sqrt{\rho_{OR}\Delta P_{OR}}}{\rho_s}$ ft/min

$\therefore V_{sb} = \frac{63.75\sqrt{\rho_{OR}\Delta P_{OR}}}{\rho_s}$ ft/min

$\therefore \Delta P_{OR}$ for isokinetic flow $= \frac{\rho_s^2 V_{sb}^2}{4064\, \rho_{OR}}$

4×47mm SYSTEM: $V_{iso} = 1.11\, V_{sb}$; $\dot{m} = 1.11\, V_{sb}\, \rho_s\, a_s\,(\text{sample})$

let $\dot{m} = (x)\, V_{sb}\, \rho_s$ lbm/min

PROBE No.	TIP I.D., in	(x)
1	0.500	0.00151
2	0.500	0.00151
3	0.501	0.00152
4	0.501	0.00152

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ERC SAMPLER

ISOKINETIC RATE $= 1.1\,(a/A)\ \text{EXH. FLOW}\ (\text{lb}_m/\text{min})$

VENTURI Δp_v for ISOKINETIC FLOW

$p_a = 29.3$: $\Delta p_v = (9.90 \times 10^{-4})\,\dot{M}_e^{1.86}$

$p_a =$ variable: $\Delta p_v = \dfrac{(0.0289)\,\dot{M}_e^{1.86}}{p_a}$

Calculations on next page

Probe No.	Tip I.D., in	(1.1 a/A)
2	0.2535	0.00297
3	0.2005	0.00186
4	0.3035	0.00426
5	0.1510	0.00106
6	0.1005	0.000467

ENGINE AIR FLOW RATE $= \dot{M}_a = 89.60\,(\Delta p\,\rho)^{0.4842}$; $\dot{M}_e = \dot{M}_a + \dot{M}_f$

for $p_a = 29.3$, $\dot{M}_a = 527.1\,(\Delta p/T)^{0.4842}$, error $< 0.5\%$ for $29.0 \le p_a \le 29.6$

for $T = 70F$, $\dot{M}_a = 25.28\,(\Delta p)^{0.4842}$, error $< 1\%$ for $60F \le T \le 80F$

	DRY GAS METER FACTORS				
No	1	2	3	4	*5
FACTOR	1.027	1.046	1.035	1.030	1.0

* this unit used on ERC sampler

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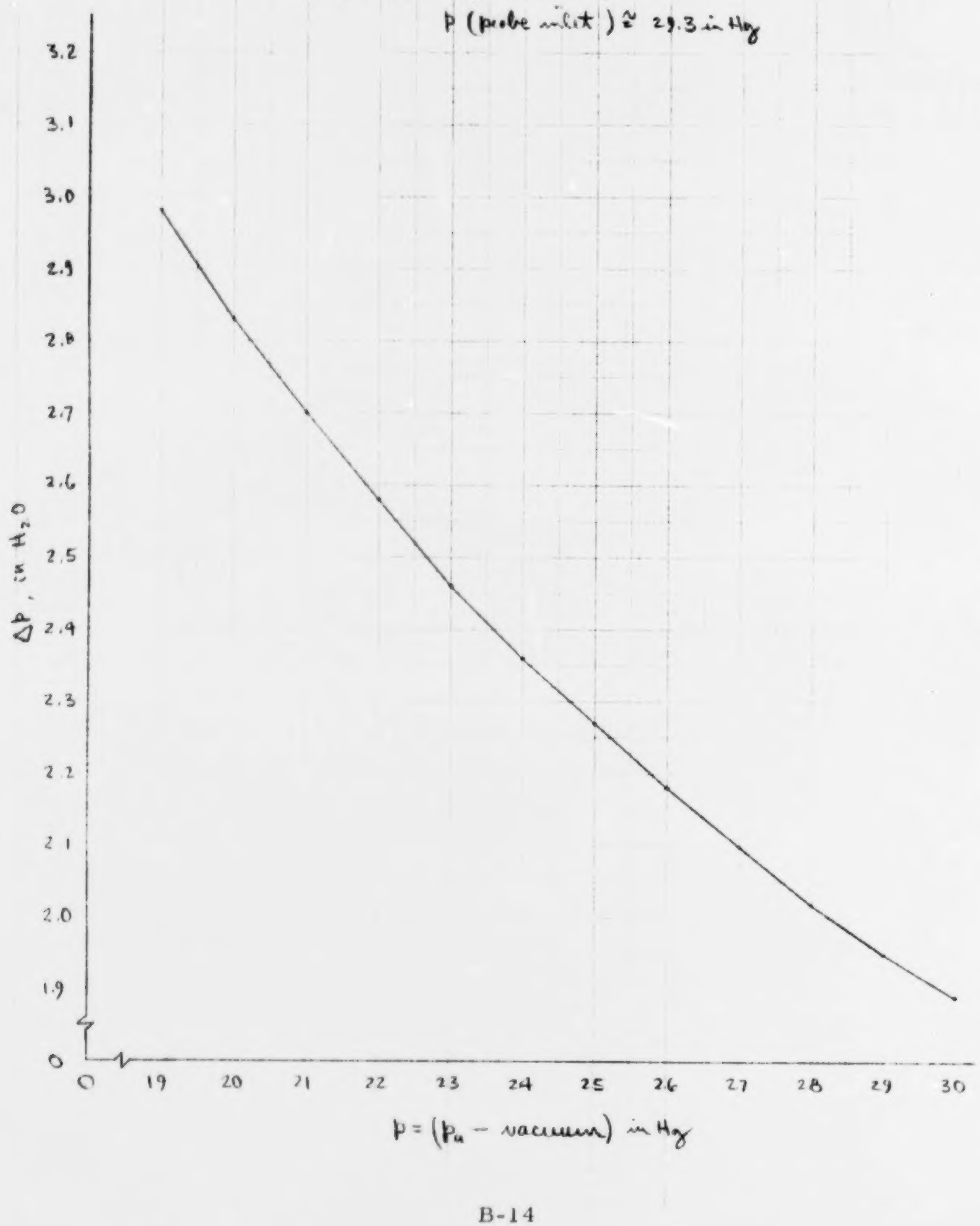
ORIFICE CALIBRATION
HI-VOL SYSTEM WITH FLUOROPORE FILTERS

CONDITIONS: T (probe inlet) ≈ 110°F
P (probe inlet) ≈ 29.3 in Hg



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DILUTION TUNNEL OPERATING INSTRUCTIONS

A. HI-VOL (8X10 FILTER) SYSTEM

1. SET Δp_{OR} (ORIFICE IN TAILPIPE) = 2.05 in H_2O WITH ENGINE OFF AND DILUTION TUNNEL BLOWER ON — SWITCH OFF SAMPLE BLOWER

2. START ENGINE AND ESTABLISH OPERATING CONDITION AS QUICKLY AS POSSIBLE

3. START SAMPLE BLOWER, COUNTER, & TIMER SIMULTANEOUSLY; CORRECT Δp_{OR} AS NECESSARY DURING RUN USING SPEED CONTROL

4. STOP SAMPLE BLOWER, COUNTER, & TIMER SIMULTANEOUSLY AT END OF RUN

B. 4 × 47 mm SYSTEM

1. SET FLOWMETERS WITH ENGINE OFF AS FOLLOWS, USING CALIBRATION CURVES FOR METERS 1 — 4 (TUNNEL BLOWER ON):

$$\left.\begin{array}{ll} \text{FLOWMETERS } 1 \,\&\, 2: & \dot{m} = 19.2/(T_s+460) \\ \text{" } 3 \,\&\, 4: & \dot{m} = 19.3/(T_s+460) \end{array}\right\} \text{TO NEAREST 1\% OF SCALE}$$

2. STOP PUMPS AND TAKE "BEFORE" DRY GAS METER READINGS, THEN START ENGINE AND ESTABLISH CONDITION AS QUICKLY AS POSSIBLE

3. START PUMPS, COUNTER, & TIMER SIMULTANEOUSLY; CORRECT FLOWMETER READINGS AS NECESSARY DURING RUN USING VALVES

4. STOP PUMPS, COUNTER, & TIMER SIMULTANEOUSLY AT END OF RUN

ERC SAMPLER INSTRUCTIONS

7/21/74

INITIAL: PUMPS ON – DUMMY FILTER – SET FLOWMETER 5 AT 70

1. ESTABLISH ENGINE OPERATING CONDITION WITH EXHAUST BACKPRESSURE BETWEEN 0.5 AND 2.0 in H_g (IF POSSIBLE) –
   – IDLE BACKPRESSURE SHOULD BE ABOUT 0.5, OTHERS 1.0 OR MINIMUM, WHICHEVER IS LARGER

2. CALCULATE EXHAUST MASS FLOW = $\dot{M}_e = \dot{M}_a$ (AIR) + $\dot{M}_f$ (FUEL)

   READ $\dot{M}_f$ from FLO-TRON; $\dot{M}_a = 89.60(\Delta p_E \rho_E)^{0.4842} = 527.1\left(\frac{\Delta p_E}{T+460}\right)^{0.4842}$, OR READ $\dot{M}_a$ from ERC GRAPH 0
   – IN THE $\dot{M}_a$ EQUATION: "Δp_E" IS ENGINE AIR ORIFICE; "T" IS ENGINE AIR INLET TEMP (⑨ ON ENGINE OPERATOR'S DIGITAL READOUT)

3. CALCULATE RAW SAMPLE $\Delta p = \Delta p_v = (9.90 \times 10^{-4})\dot{M}_e^{1.86}$ OR READ Δp_v from ERC GRAPH 1

4. SET DILUTE SAMPLE FLOW RATE AT 50 ACFM USING ERC GRAPH 2 AT T_{ds} (④ ON TUNNEL DIGITAL READOUT)

5. CALCULATE PRIMARY DILUTION $\Delta p = \Delta p_{da} = (1.94 \times 10^{-6})\frac{T_E^{4/3}}{T_{da}^{1/3}}\dot{M}_e^2$ OR READ Δp_{da} from ERC GRAPH 3

6. SET Δp_v AND Δp_{da} USING SHUTTER AND DILUTION AIR CONTROL

7. CALCULATE RAW SAMPLE FLOW RATE = $\dot{m}_s = 0.00186\,\dot{M}_e$ OR READ $\dot{m}_s$ from ERC GRAPH 4

8. TURN OFF 1 CFM SAMPLE PUMP AND INSTALL CORRECT FLUOROPORE FILTER

9. RECORD DRY GAS METER READING

10. SIMULTANEOUSLY START 1 CFM SAMPLE PUMP AND TIMER; RESET No. 5 FLOWMETER $(1\ \mathrm{ACFM})_{ds}$ AND No. 5 CALIBRATION CURVE; AND RECORD DATA AT INDICATED INTERVALS ON SAMPLER OP'S. SHEET

11. SHUT DOWN 1 CFM PUMP AND TIMER WHEN INDICATED OR IF FILTER PLUG

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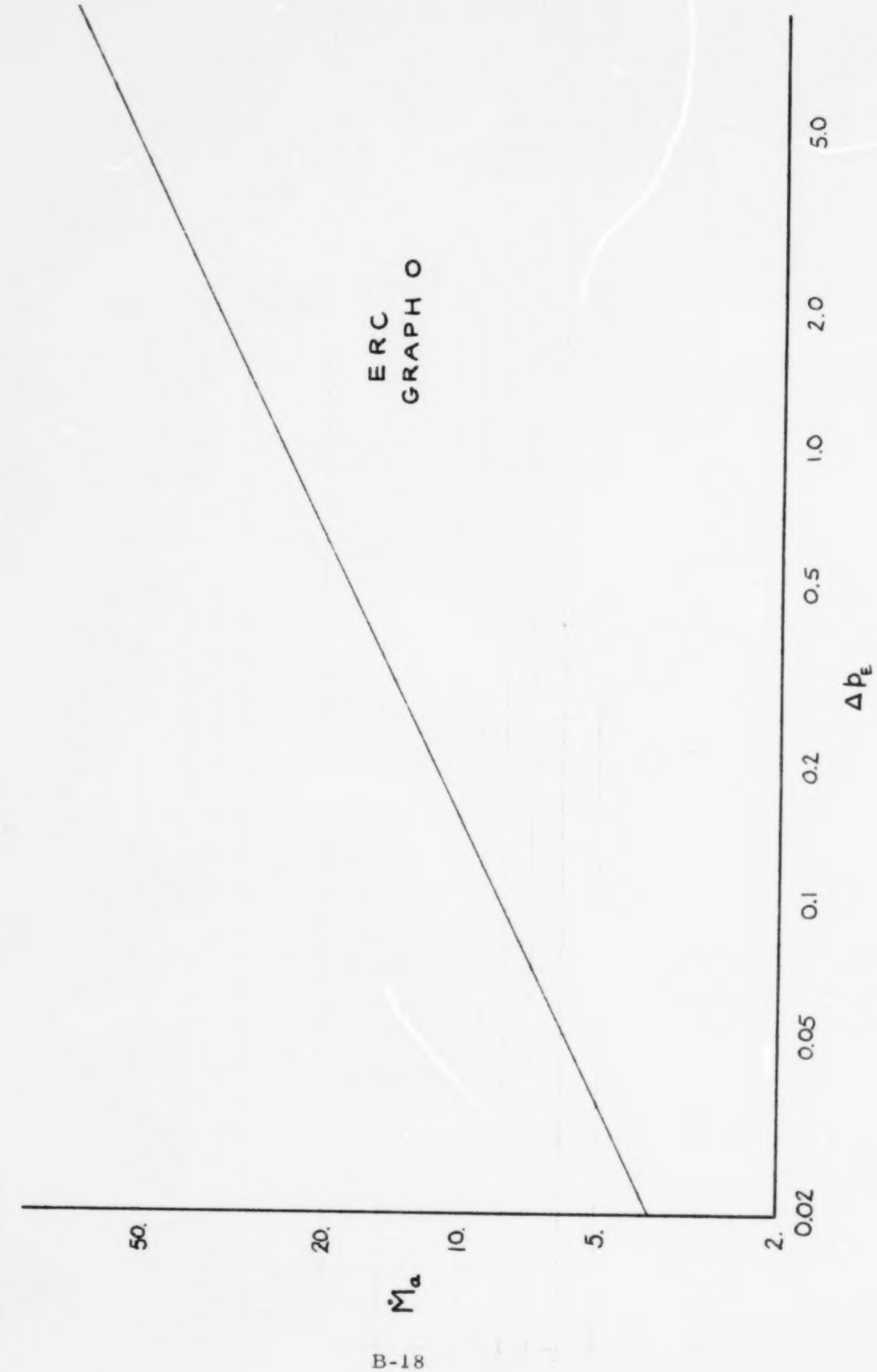
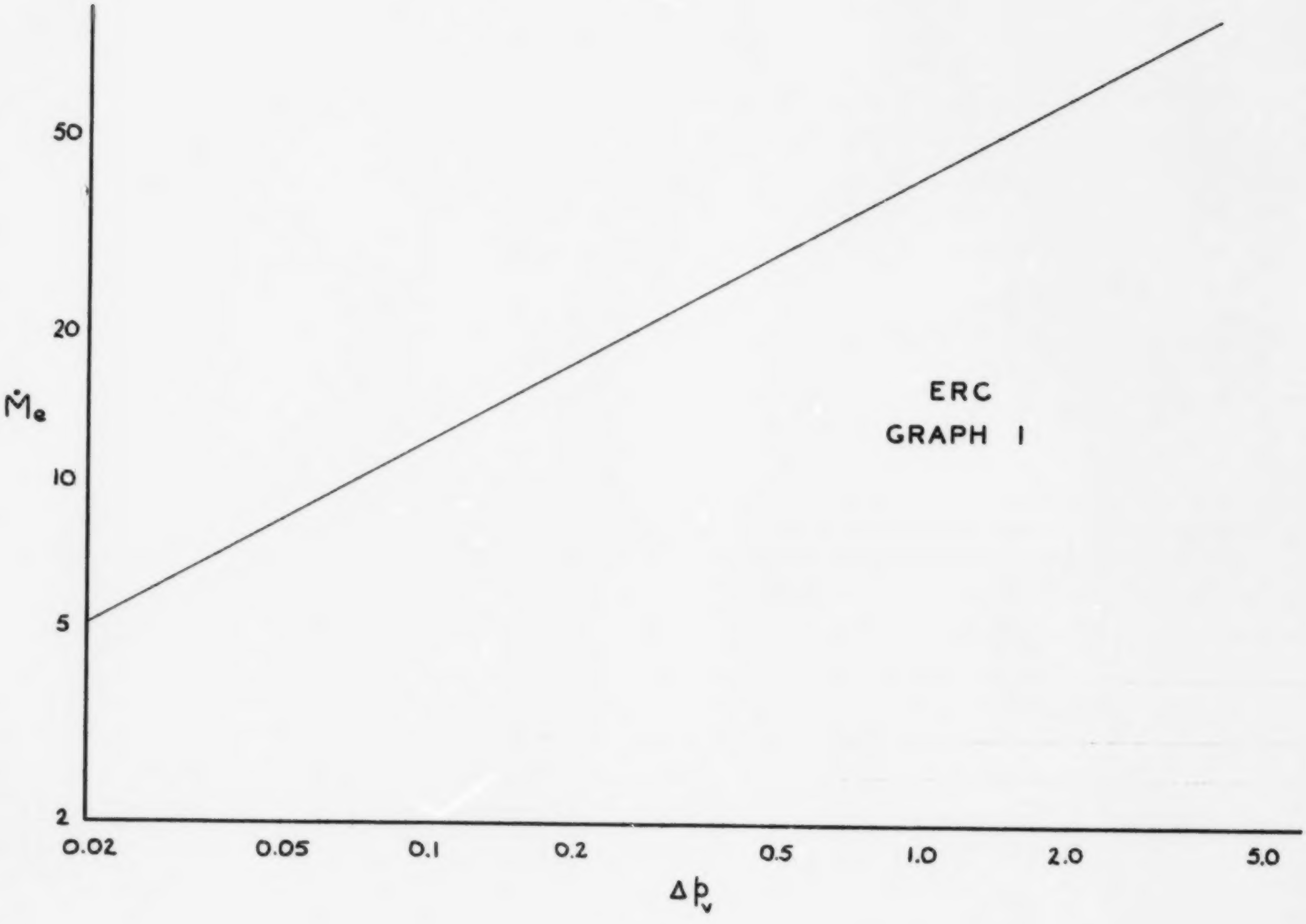
GENERAL CONDITIONS AND LIMITS

1. $29.0 \text{ in Hg} \le p_a \le 29.6 \text{ in Hg}$
2. raw sample temperature ② $50\text{F} \le T_v \le 300\text{ F}$
3. ERC dilution air temperature ③ $60\text{F} \le T_{da} \le 80\text{F}$
4. ERC sampling nozzle I.D. = 0.2005 in
5. EXHAUST PIPE I.D. (upstream of muffler) = 4.875 in
6. ERC SAMPLE LINE CONFIGURATION — 50 inch line 0.5 inch O.D. SS; 6 inch line 0.25 inch O.D. SS; 30 inch standard ERC sample line


ERC
GRAPH O
$\dot{M}_a$
2.
5.
10.
20.
50.
0.02
0.05
0.1
0.2
0.5
1.0
2.0
5.0
Δp_E



ERC
GRAPH I

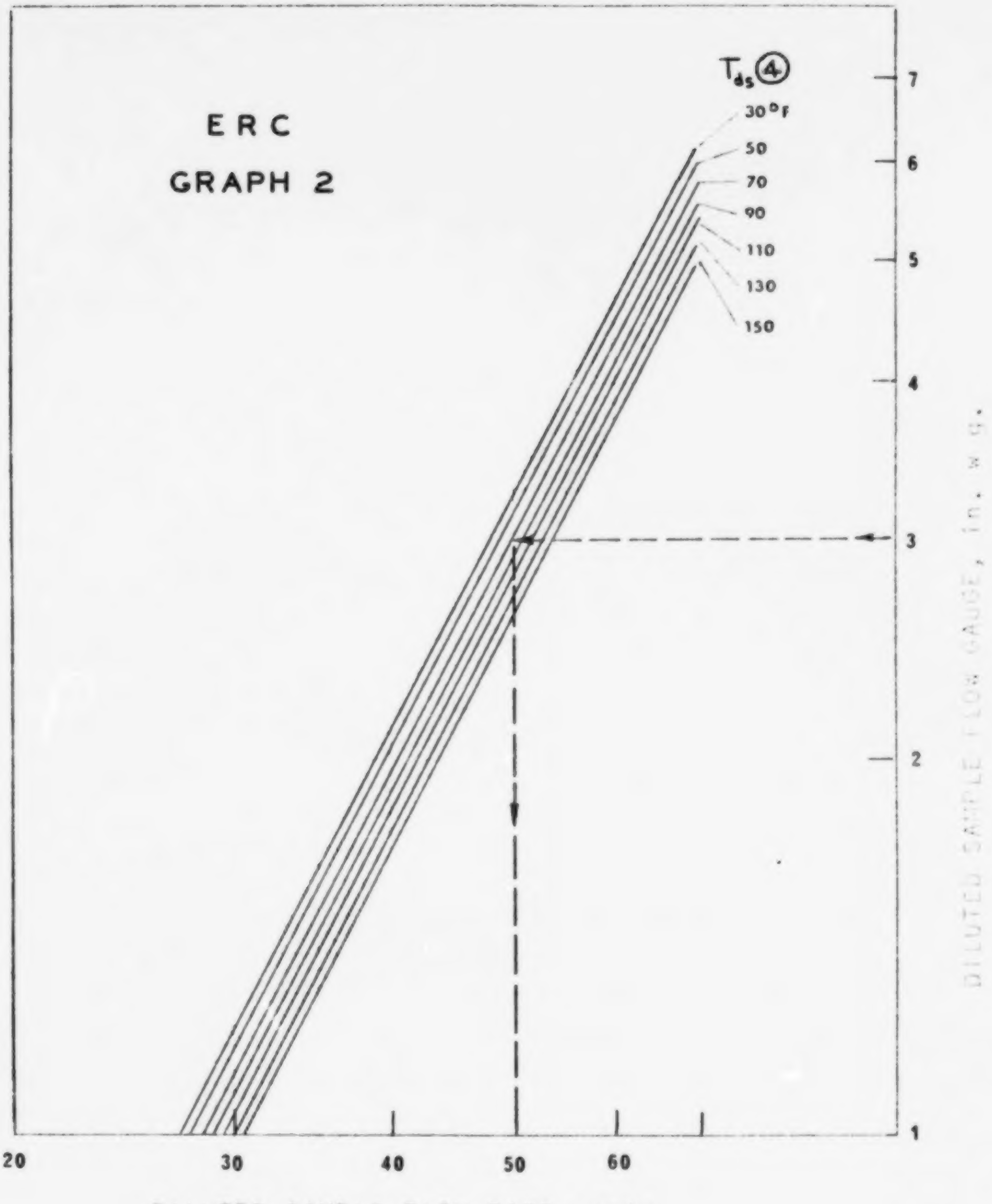
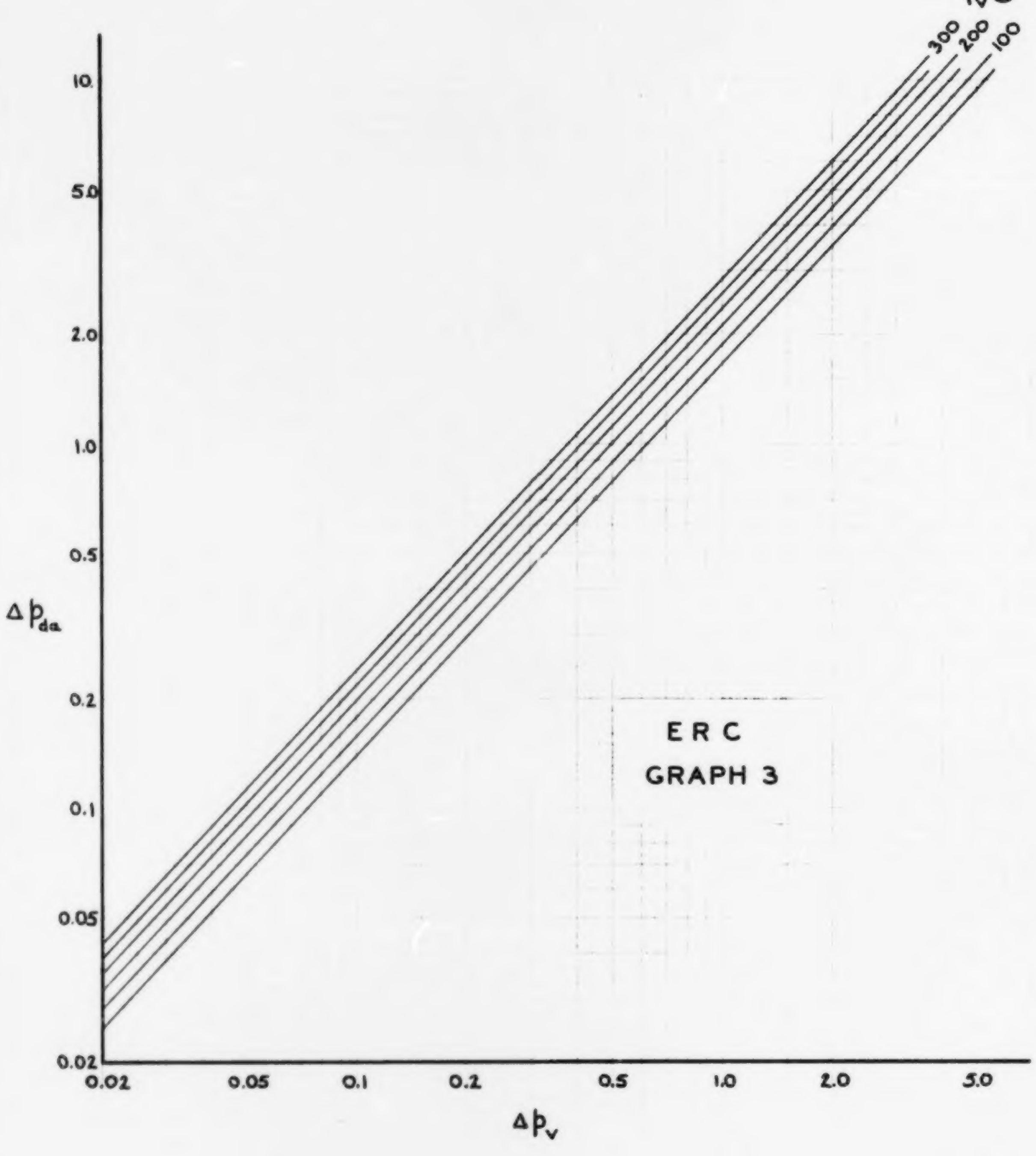
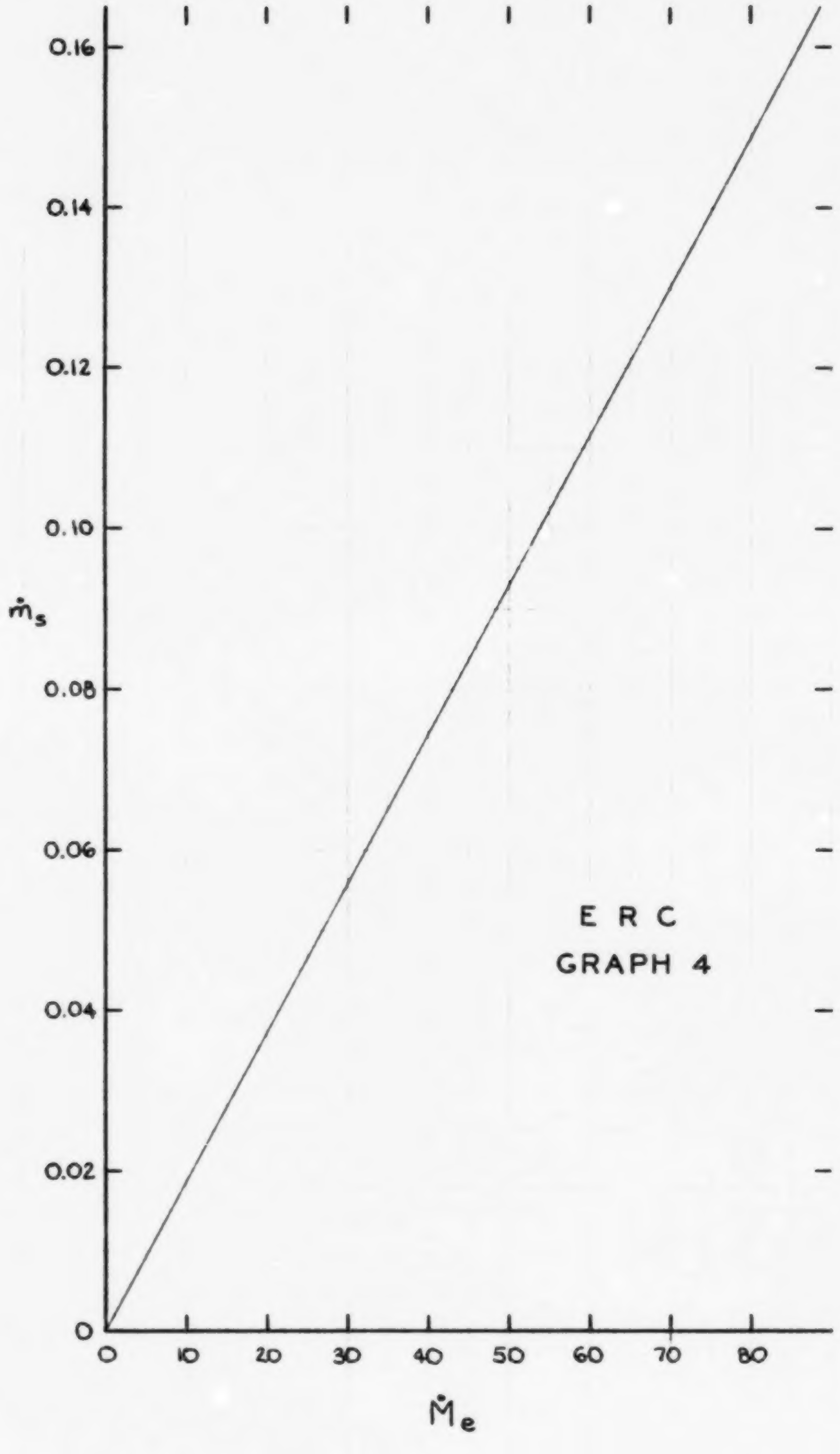
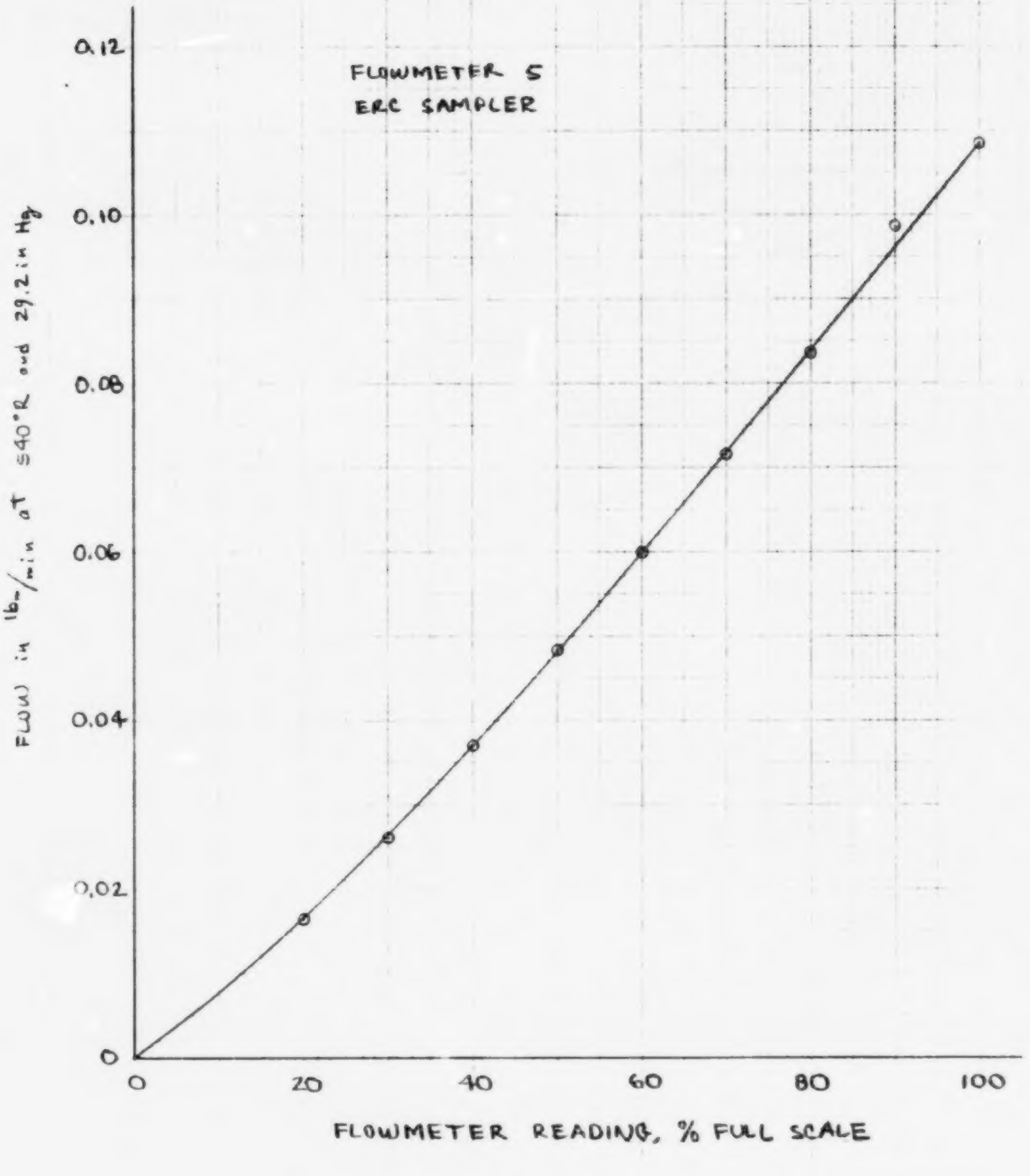


Figure 15. Diagram of the Diluted Sample Flow Rate


T_v ②
300
200
100
Δp_{da}
10.
5.0
2.0
1.0
0.5
0.2
0.1
0.05
0.02
0.02
0.05
0.1
0.2
0.5
1.0
2.0
5.0
Δp_v
ERC
GRAPH 3


0.16
0.14
0.12
0.10
$\dot{m}_s$
0.08
0.06
0.04
0.02
0
0
10
20
30
40
50
60
70
80
$\dot{M}_e$
E R C
GRAPH 4



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HARE

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EXTRAPOLATION OF VENTURI CURVES - ERC

DATA $T_v = 100F$ $p_a \equiv 29.3$ in Hg $\therefore \rho \equiv 0.0694$ Q in ACFM, $\dot{m}$ in lbm/min

Δp	1	2	4	8	10
Q	(1.118) 1.11	1.64	2.39	3.46	(3.909) 3.89
$\dot{m}$	(0.0776) 0.0770	0.114	0.166	0.240	(0.2714) 0.270

$Q = a(\Delta p)^b$ $\dot{m} = c(\Delta p)^d$

$a = 1.118$ $c = 0.07761$

$b = 0.5438$ $d = 0.5436$

$r^2 = 0.9999$ $r^2 = 0.9998$

DATA $T_v = 200F$ $p_a \equiv 29.3$ in Hg $\therefore \rho \equiv 0.0589$

Δp	1	2	4	8	10
Q	(1.233) 1.22	1.81	2.62	3.77	(4.258) 4.23
$\dot{m}$	(0.0740) 0.0718	0.112	0.154	0.222	(0.2510) 0.249

$Q = a(\Delta p)^b$ $\dot{m} = c(\Delta p)^d$

$a = 1.233$ $c = 0.07405$

$b = 0.5382$ $d = 0.5302$

$r^2 = 0.9997$ $r^2 = 0.9965$

DATA $T_v = 300F$ $p_a \equiv 29.3$ in Hg $\therefore \rho \equiv 0.0511$

Δp	1	2	4	8	10
Q	(1.335) 1.32	1.96	2.83	4.07	(4.588) 4.55
$\dot{m}$	(0.0785) 0.0777	0.115	0.167	0.240	(0.2705) 0.268

$Q = a(\Delta p)^b$ $\dot{m} = c(\Delta p)^d$

$a = 1.335$ $c = 0.07852$

$b = 0.5360$ $d = 0.5371$

$r^2 = 0.9996$ $r^2 = 0.9996$

ALL 15 POINTS $\dot{m} = c(\Delta p)^d$ $(\Delta p)_1 = 0.0767$

$c = 0.07670$ $(\Delta p)_{10} = 0.2641$

$d = 0.5370$

$r^2 = 0.9942$

error ±1.1% from $29.0 \le p_a \le 29.6$

$$\therefore \underline{\underline{\dot{m} = 0.0767(\Delta p)^{0.537}}} \text{ at } 29.3 \text{ in Hg},\ 100 \le T_v \le 300$$

for variable p_a: $\underline{\underline{\dot{m} = 0.0767\left(\frac{\Delta p\ p_a}{29.3}\right)^{0.537}}}$

for isokinetic flow, $p_a = 29.3$, probe tip I.D = 0.2005 in

$$\Delta p = (13.04\ \dot{m})^{1.86} = (0.02425\ \dot{M}_e)^{1.86} = (9.90\times10^{-4})\dot{M}_e^{1.86}$$

for isokinetic flow, variable p_a, probe tip I.D = 0.2005 in

$$\Delta p = \frac{(79.95\ \dot{m})^{1.86}}{p_a} = \frac{(0.1486\ \dot{M}_e)^{1.86}}{p_a} = \frac{(0.0289)\dot{M}_e^{1.86}}{p_a}$$

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CALCULATION OF Δp_{da} IN TERMS OF KNOWN QUANTITIES

BASIC EQ: $\Delta p_{da}(\text{psi}) = 1.3\,\rho_{da}\dfrac{V_{da}^2}{2g}$; ρ in $\dfrac{\text{lb}_m}{\text{ft}^3}$; V in $\dfrac{\text{ft}}{\text{sec}}$; $g = 32.2\,\dfrac{\text{ft lb}_m}{\text{lb}_f\ \text{sec}^2}$

$$\Delta p_{da}(\text{in } H_2O) = 1.3\,\rho_{da}\frac{V_{da}^2}{2g} \times \frac{g\ \text{lb}_f\ \text{sec}^2}{32.2\ \text{ft lb}_m} \times \frac{27.69\ \text{in } H_2O}{1\ \text{psi}} = 0.559\,\rho_{da}(V_{da})^2$$

check: $\rho_{da} = 0.07$, $V_{da} = 6.25$; $\Delta p_{da} = 1.52$ in H_2O ✓ (reasonable)

$V = Q/A$ $\therefore$ $\Delta p_{da} = 0.559\,\rho_{da}\left(\dfrac{Q_{da}}{A}\right)^2$; Q in $\dfrac{\text{lb}_m}{\text{sec}}$; A in $\text{ft}^2 = A_{da} = A_s = 0.00267\ \text{ft}^2$

to get Q to $\dfrac{\text{lb}_m}{\text{min}}$: $\Delta p_{da} = 0.559\,\rho_{da}\left(\dfrac{Q_{da}}{A}\right)^2\left(\dfrac{1\ \text{min}}{60\ \text{sec}}\right)^2 = (1.55\times10^{-4})\,\rho_{da}\left(\dfrac{Q_{da}}{A}\right)^2$

FOR $KE_{da} = KE_s$: $\rho_s Q_s V_s^2 = \rho_{da} Q_{da} V_{da}^2$; $V = Q/A$; $A_{da} = A_s$

$$\therefore\ \rho_s Q_s^3 = \rho_{da} Q_{da}^3 \qquad \therefore\ Q_{da} = Q_s\left(\rho_s/\rho_{da}\right)^{1/3}$$

$$\therefore\ \Delta p_{da} = (1.55\times10^{-4})\,\rho_{da}\frac{Q_s^2\,\rho_s^{2/3}}{A^2\,\rho_{da}^{2/3}} \quad ; \quad Q_s = \dot m_s/\rho_s$$

$$\therefore\ \Delta p_{da} = (1.55\times10^{-4})\,\frac{\rho_{da}^{1/3}}{\rho_s^{4/3}}\,\frac{\dot m_s^2}{A^2} = (21.74)\frac{(\rho_{da})^{1/3}}{(\rho_s)^{4/3}}\,\dot m_s^2$$

FOR $\rho = 1.326\,\dfrac{p}{T}$, p in in Hg , T in °R ; assume $p_s = p_{da} = p_a$

$$\therefore\ \underline{\underline{\Delta p_{da}}} = (21.74)\frac{\left(1.326\,\frac{p_a}{T_{da}}\right)^{1/3}}{\left(1.326\,\frac{p_a}{T_s}\right)^{4/3}}(\dot m_s^2) = \underline{\underline{(16.40)\,\frac{(T_s)^{4/3}}{p_a\,(T_{da})^{1/3}}(\dot m_s)^2}}$$

FOR $p_a = 29.3$

$$\boxed{\underline{\underline{\Delta p_{da} = (0.560)\frac{(T_s)^{4/3}}{(T_{da})^{1/3}}(\dot m_s)^2}}}$$

FURTHER: $\dot m_s = 0.00186\ \dot M_e$ for 0.2005 in I.D. sampling nozzle

$$\therefore\ \underline{\underline{\Delta p_{da}}} = (16.40)\frac{(p_a/T_{da})^{1/3}}{(p_a/T_s)^{4/3}}(0.00186\,\dot M_e)^2 = \underline{\underline{(5.67\times10^{-5})\frac{(p_a/T_{da})^{1/3}}{(p_a/T_s)^{4/3}}\,\dot M_e^2}}$$

FOR $p_a = 29.3$; $\underline{\underline{\Delta p_{da} = (1.94\times10^{-6})\dfrac{(T_s)^{4/3}}{(T_{da})^{1/3}}\,\dot M_e^2}}$

NOTE: T_s USED HERE
IS T_v ② ON
DATA SHEETS

NOTE: T_s USED HERE
IS T_v ② ON
DATA SHEETS

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TO GENERATE Δp_{da} vs Δp_v CURVES; p_a, T_s, T_{da} AS PARAMETERS

$p_a = 29.3$: $\Delta p_{da} = (1.94 \times 10^{-6}) \dfrac{T_s^{4/3}}{T_{da}^{1/3}} \dot{M}_e^2$ $\qquad \Delta p_v = (0.02425\, \dot{M}_e)^{1.86} = (9.90 \times 10^{-4})\, \dot{M}_e^{1.86}$

$\therefore \dot{M}_e = 41.24\, (\Delta p_v)^{0.537}$ $\qquad \therefore \Delta p_{da} = (3.30 \times 10^{-3}) \dfrac{T_s^{4/3}}{T_{da}^{1/3}} (\Delta p_v)^{1.074}$

$T_{da} = 530\,R$ (70F) $\qquad \therefore \Delta p_{da} = (4.08 \times 10^{-4})\, T_s^{4/3} (\Delta p_v)^{1.074} = K (\Delta p_v)^{1.074}$

T_s	K	$\Delta p_{da}\vert_{\Delta p_v = 0.2}$	$\Delta p_{da}\vert_{\Delta p_v = 1}$	$\Delta p_{da}\vert_{\Delta p_v = 3}$
510	1.662	0.295	1.662	5.41
560	1.882	0.334	1.882	6.12
610	2.110	0.375	2.110	6.87
660	2.343	0.416	2.343	7.62
710	2.583	0.459	2.583	8.41
760	2.828	0.502	2.828	9.20

$T_{da} = 540\,R$ (80F) $\qquad \therefore \Delta p_{da} = (4.05 \times 10^{-4})\, T_s^{4/3} (\Delta p_v)^{1.074} = K (\Delta p_v)^{1.074}$

T_s	K
510	1.651
560	1.871
610	2.096
660	2.329
710	2.567
760	2.811

$T_{da} = 550\,R$ (90F) $\qquad \therefore \Delta p_{da} = (4.03 \times 10^{-4})\, T_s^{4/3} (\Delta p_v)^{1.074} = K (\Delta p_v)^{1.074}$

T_s	K
510	1.641
560	1.859
610	2.084
660	2.314
710	2.551
760	2.793

NOTE: T_s USED HERE
IS T_v② ON DATA
SHEETS

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$p_a = 29.3$ (cont'd).
$T_{da} = 520$ R (60F)

$\therefore \Delta p_{da} = (4.10 \times 10^{-4})\ T_s^{4/3} (\Delta p_v)^{1.074} = K (\Delta p_v)^{1.074}$

T_s	K
510	1.672
560	1.894
610	2.123
660	2.358
710	2.599
760	2.846

$p_a = 29.2$: $\Delta p_{da} = (1.94 \times 10^{-6}) \dfrac{T_s^{4/3}}{T_{da}^{1/3}} \dot{M}_e^2$ $\qquad \Delta p_v = (9.90 \times 10^{-4})\ \dot{M}^{1.86}$

NO CHANGE (ROUNDING ERROR ONLY, < 0.1%)

SO – USE FIGURES FOR 70F (WITHIN 1% $60F \le T_{da} \le 80F$) AND
29.3 in Hg (WITHIN 1% $29.0 \le p_a \le 29.6$)

NOTE: T_s USED HERE
IS T_v ② ON DATA
SHEETS

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VERIFICATION OF Δp_v vs Δp_{da} RELATIONSHIP

METHOD: CHOOSE T_s & T_{da} EQUAL, THEN $\rho_s = \rho_{da}$ AND $V_s = V_{da}$, etc.

$Q_s = Q_{da} = 1.0$ CFM $V_s = V_{da} = 6.24$ ft/sec $\rho_{da} = 0.0733 \frac{\text{lbm}}{\text{ft}^3}$ @ 29.3 & 70F

$\Delta p_{da} = 0.559 \rho_{da}(V_{da})^2$ from ERC manual (Δp in in H_2O, ρ in lbm/ft³, V in ft/sec)

$\therefore \Delta p_{da} = 1.596$ in H_2O

from my equations: $\Delta p_v = (13.04 \dot{m})^{1.86} = (13.04 \times 0.0733)^{1.86} = 0.919$ in H_2O

from my graph: $\Delta p_{da} \cong 1.58$ in H_2O — VERIFIED

$Q_s = Q_{da} = 2.0$ CFM $V_s = V_{da} = 12.5$ ft/sec $\rho_{da} = 0.0733 \frac{\text{lbm}}{\text{ft}^3}$ @ 29.3 & 70F

$\Delta p_{da} = 0.559 \rho_{da}(V_{da})^2 = 6.402$ in H_2O

$\Delta p_v = (13.04 \dot{m})^{1.86} = (13.04 \times 0.147)^{1.86} = 3.35$ in H_2O

from my graph: $\Delta p_{da} \cong 6.35$ in H_2O — VERIFIED

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INLET AIR ORIFICE CALIBRATION

	RUN 1				RUN 2			
$\Delta p_{ORIFICE}$	Q, UNCORR.	p CORR.	T CORR.	$\dot{m}_{STD}$, lbm/min	Q, UNCORR.	p CORR.	T CORR.	$\dot{m}_{STD}$, lbm/min
0.17	128.	0.9865	0.9642	9.11	131.	0.9840	0.9867	9.52
0.2	162.	0.9864	0.9737	11.65	165.	0.9839	0.9867	11.99
0.4	235.	0.9862	0.9737	16.89	232.	0.9837	0.9834	16.80
0.6	271.	0.9860	0.9737	19.48	276.	0.9835	0.9834	19.98
0.8	316.	0.9858	0.9737	22.71	318.	0.9833	0.9834	23.02
1.0	346.	0.9856	0.9802	25.02	351.	0.9832	0.9802	25.32
1.2	383.	0.9855	0.9770	27.60	380.	0.9830	0.9802	27.41
1.4	409.	0.9854	0.9737	29.38	408.	0.9829	0.9834	29.52
1.6	438.	0.9852	0.9737	31.45	434.	0.9827	0.9802	31.29
1.8	468.	0.9850	0.9737	33.60	475.	0.9826	0.9802	34.25
2.0	499.	0.9849	0.9705	35.70	500.	0.9824	0.9802	36.04
2.5	578.	0.9841	0.9642	41.07	566.	0.9820	0.9802	40.78
3.0	602.	0.9842	0.9642	42.76	612.	0.9817	0.9802	44.08
3.5	661.	0.9839	0.9674	47.10	664.	0.9813	0.9770	47.65
4.0	702.	0.9837	0.9674	50.01	704.	0.9812	0.9737	50.35
4.5	739.	0.9835	0.9674	52.63	728.	0.9810	0.9737	52.05
5.0	788.	0.9831	0.9705	56.28	779.	0.9806	0.9770	55.87
5.5	817.	0.9830	0.9705	58.34	812.	0.9805	0.9802	58.42
6.0	843.	0.9825	0.9705	60.17	849.	0.9801	0.9802	61.06
6.5	875.	0.9825	0.9705	62.45	898.	0.9800	0.9770	64.36
7.0	935.	0.9823	0.9674	66.51	925.	0.9795	0.9737	66.04

$\rho_{STD} = 0.074856$ lbm/ft³

CALIBRATION OF ENGINE INLET
AIR ORIFICE

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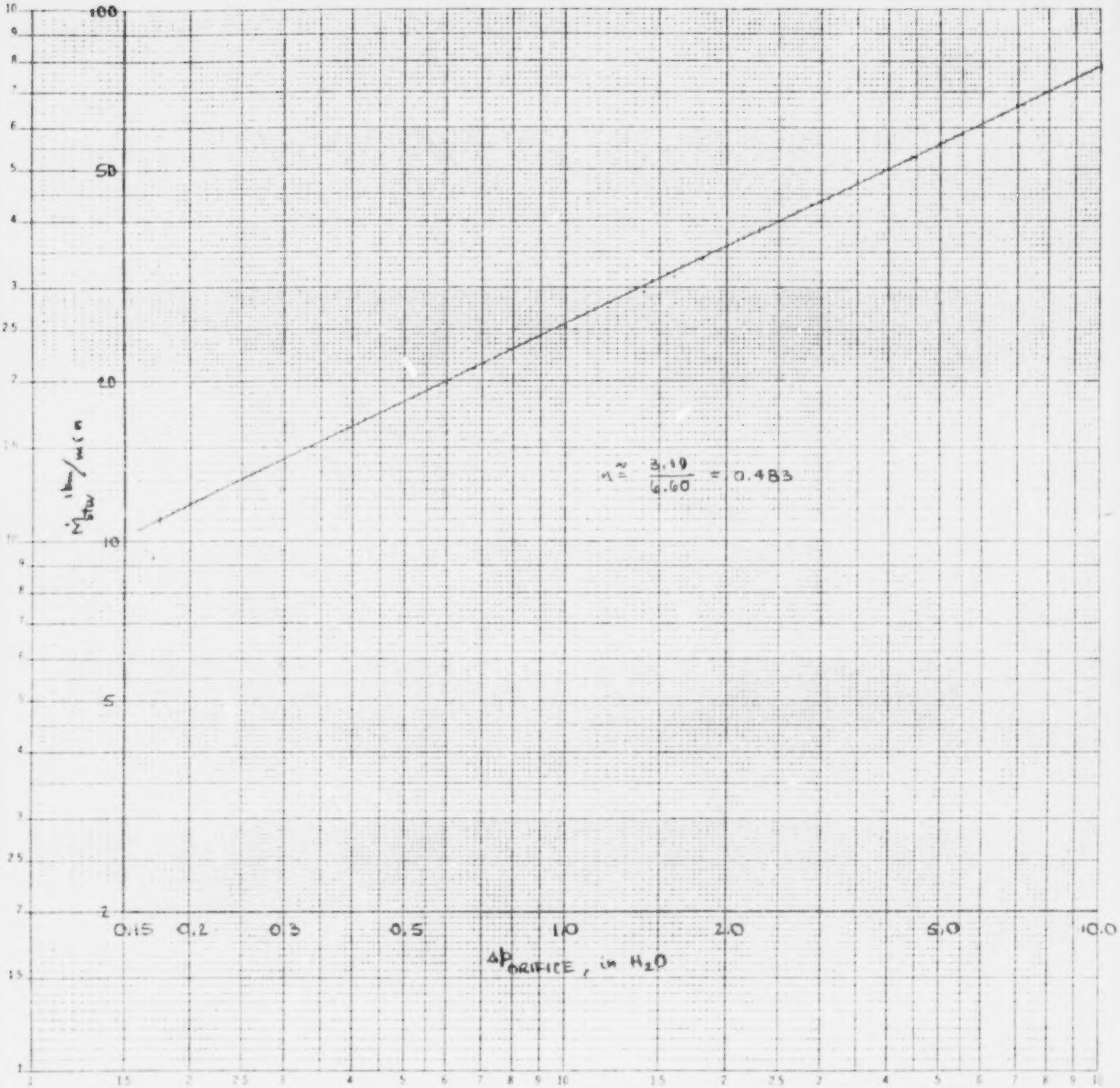

(estimated line: $\log_{10} \dot{M}_{STD} = \log_{10} 25.7 + 0.483 \log_{10} \Delta p$

$\therefore \dot{M}_{STD} = 25.7 (\Delta p)^{0.483}$)

actual line $\dot{M}_{STD} = 25.53 (\Delta p)^{0.4842}$

APPENDIX C

DATA REDUCTION

SAMPLER OPERATOR ____________ DATE / / RUN ____

FOR MULTIMODE RUNS

MODE	TIME (sec) AT		ENGINE		TEMP'S, °F				Δp, in H_2O			FLOWMETER R.					ORIFICE
	START	END	RPM	LOAD, %	T_P ①	T_V ②	T_{DA} ③	T_{DS} ④	PRIM. DIL.	RAW S. (VENTURI)	DIL. SAMPLE	1	2	3	4	5	Δp
1																	
2																	
3																	
4																	
5																	
6																	
7																	
8																	
9																	
10																	
11																	
12																	
13																	

FOR SINGLE-MODE RUNS (STEADY-STATE)

RPM = ______ % LOAD = ______ LOAD(lb_f) = ______

	TIME,	TIME,	TEMP'S., °F				Δp, in H_2O			FLOWMETER R.					ORIFICE
	sec	min	T_P ①	T_V ②	T_{DA} ③	T_{DS} ④	PRIM. DIL.	RAW S. (VENTURI)	DIL. SAMPLE	1	2	3	4	5	Δp
1															
2															
3															
4															
5															
6															
7															
8															
9															
10															
11															
12															
13															

FILTER No. BY POSITION	
1	FP47-
2	A47-
3	A47-
4	A47-
5	FP47-
R	AR-

	DRY GAS METER	
	BEFORE	AFTER
1		
2		
3		
4		
5		

ENGINE ____________ ERC PROBE TIP I.D. ______

FOR MULTIMODE RUNS

	TIME (sec) AT		ENGINE		TEMP'S., °F					BLOWER		VALVE TURNS CLD		NO_x RAW		NO_x DILUTE	
MODE	START	END	RPM	LOAD, %	T_A ⑧	T_S ⑨	T_F ⑩	T_{OR} ⑪	T_B ⑫	Δp	P_s	LARGE	SMALL	RANGE	CHART	RANGE	CHART
1																	
2																	
3																	
4																	
5																	
6																	
7																	
8																	
9																	
10																	
11																	
12																	
13																	

TUNNEL BLOWER COUNTS		,			.
SAMPLING TIME, sec	,			.	

FOR SINGLE-MODE RUNS (STEADY-STATE)

RPM = ______ % LOAD = ______ LOAD (lb_f) = ______

	TIME, sec	TIME, min	TEMP'S., °F					BLOWER		VALVE TURNS CLD.		NO_x RAW		NO_x DILUTE	
			T_A ⑧	T_S ⑨	T_F ⑩	T_{OR} ⑪	T_B ⑫	Δp	P_s	LARGE	SMALL	RANGE	CHART	RANGE	CHART
1															
2															
3															
4															
5															
6															
7															
8															
9															
10															
11															
12															

ENGINE ______________________ FILTER(S) ______________________

ENGINE OPERATOR ____________________ DATE __/__/__ RUN ____

FOR MULTIMODE RUNS

	TIME (sec) AT		ENGINE			INTAKE AIR		RESTRICTIONS		FUEL,
MODE	START	END	RPM	LOAD, %	LOAD, lb_f	ΔP_E, in H_2O	T_E, °F	INTAKE, in H_2O	EXHAUST, in Hg	lb_m/hr
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										
13										

FOR SINGLE-MODE RUNS (STEADY-STATE)

RPM = ______ %LOAD = ______ LOAD(lb_f) = ________

	TIME,	TIME,	INTAKE AIR		RESTRICTIONS		FUEL,
	sec	min	ΔP_E, in H_2O	T_E, ⑨ °F	INTAKE, in H_2O	EXHAUST, in Hg	lb_m/hr
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							

ENGINE ______________________________ FUEL __________ p_a = ______ in Hg

WET BULB = ____ °F DRY BULB = ____ °F EXH. SYSTEM ________________

FILTER(S) ____

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DATA REDUCTION PROCEDURES

DATA

ONE VALUE PER TEST

wt. of particulate in g = G_{AR}, G_{47j}, G_{ERC}

total sampling time = (time) = $\sum$(time)$_i$, sec

blower counts = C_B

blower rate in counts/sec = R = C_B/(time)

atmospheric pressure = p_a (in Hg)

initial dry gas meter readings = V_{1j}, ft^3

final " = V_{2j}, ft^3

number of modes = N

ONE VALUE PER MODE

raw NO_x concentration = $(NO_x)_R$, pp–

dilute NO_x concentration = $(NO_x)_D$, pp–

engine air orifice Δp = Δp_E, in H_2O

engine air temperature = T_E, °F

blower inlet temperature = T_B, °F

time in mode = (time)$_i$, sec

engine fuel rate = $\dot{M}_f$, lbm/hr

hi-vol orifice Δp = Δp_{OR}, in H_2O

hi-vol orifice temperature = T_{OR}, °F

EQUATIONS

$$\rho_E \cong 1.326\, p_a/(T_E + 460) \ \text{lbm/ft}^3$$

$$\dot{M}_a = 89.60\,(\Delta p_E\, \rho_E)^{0.4842} \ \text{lbm/min}$$

$$\dot{M}_e = \text{engine exhaust mass flow} = \dot{M}_a + \dot{M}_f/60 \ (\text{lbm/min})$$

$$E = \text{exhaust flow through tunnel} = E+D\left(\frac{E}{E+D}\right) - (E+D)\,\frac{(NO_x)_D}{(NO_x)_R}$$

FOR HI-VOL SAMPLES ONLY

$$\dot{M}_{OR} = \text{mass flow of hi-vol sample} = 4.65\,(\Delta p_{OR}\, \rho_{OR})^{0.5} \ \text{lbm/min} \ ; \ \rho_{OR} \cong 1.326\, p_a/(T_{OR}+460)$$

$$\text{particulate omission rate } (\text{g/hr}) = \frac{3600\, G_{AR}}{(\text{time})} \frac{(\text{TOTAL EXH. MASS})}{\left(\begin{array}{c}\text{TOTAL RAW EXH.}\\ \text{MASS FILTERED}\end{array}\right)} = \frac{3600\, G_{AR}}{(\text{time})} \frac{\sum_{i=1}^{N} (\dot{M}_e)_i (\text{time})_i}{\sum_{i=1}^{N} (\dot{M}_{OR})_i (\text{time})_i \left(\frac{E}{E+D}\right)_i}$$

$$\text{ticulate concentration } (\mu\text{g/m}^3 \ @\ 29.92 \text{ in Hg} ;\ 21\,^\circ\text{C}) = \frac{1.586 \times 10^8\, G_{AR}}{\sum_{i=1}^{N} (\dot{M}_{OR})_i (\text{time})_i \left(\frac{E}{E+D}\right)_i}$$

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FOR 47-mm (TUNNEL) SAMPLES ONLY

integrated mass flow through filter j = m_j (lb_m)

m_1(filter 1) = 0.0753 $(V_{21}-V_{11})$ lb_m

m_2(filter 2) = 0.0767 $(V_{22}-V_{12})$ lb_m

m_3(filter 3) = 0.0759 $(V_{23}-V_{13})$ lb_m

m_4(filter 4) = 0.0755 $(V_{24}-V_{14})$ lb_m

$$\text{particulate emission rate } (g/hr) = \frac{60\ G_{47j}}{(time)} \frac{\sum_{i=1}^{N} (\dot{M}_e)_i\,(time)_i}{\frac{m_j}{(time)} \sum_{i=1}^{N} (time)_i \left(\frac{E}{E+D}\right)_i}$$

$$= \frac{60\ G_{47j}}{m_j} \frac{\sum_{i=1}^{N} (\dot{M}_e)_i\,(time)_i}{\sum_{i=1}^{N} (time)_i \left(\frac{E}{E+D}\right)_i}$$

$$\text{particulate concentration } (mg/m^3 \text{ @ } 29.92\,\text{in Hg}\ \&\ 21°C) = \frac{(2.643\times10^{6})\ G_{47j}\ (time)}{m_j \sum_{i=1}^{N} (time)_i \left(\frac{E}{E+D}\right)_i}$$

FOR ERC 47-mm SAMPLES ONLY (steady-state conditions only)

$$\text{particulate emission rate } (g/hr) = \frac{(9.68\times10^{7})\ G_{ERC}}{(time)}$$

$$\text{particulate concentration } (mg/m^3 \text{ @ } 29.92\,\text{in Hg}\ \&\ 21°C) = \frac{(4.263\times10^{12})\ G_{ERC}}{\dot{M}_e\ (time)}$$

PAGE 1 OF 2

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80

RUN NO.	SEQ	DATE	RPM	LOAD	FILTER CODES BY POSITION NO. 1 – R	NO. 2	NO. 3	NO. 4	NO. 5	ENGINE CODE
d – d d d		mm / d d / y y	d d d d	d d d	a a d d – d d d d d					
–	0 1	/ /			–	–	–	–	–	

	FUEL CODE	PARTICULATE WEIGHTS GAR OR G471	G472	G473	G474	GERC	PA	CB	TOTAL TIME		N
	d d d	d . d d d d d d					d d . d d	d d d d d d	d d d d . d		d d
	0 2 E M F										

		DRY GAS METER READINGS V11	V21	V12	V22	V13	V23	V14	V24
		d d d . d d d							
	0 3								

		TIME IN MODE 1	2	3	4	5	6	7	8	9	10	11	12	13
		d d d												
	0 4 T I M E													

		ORIFICE TEMP. BY MODE 1	2	3	4	5	6	7	8	9	10	11	12	13
		d d d												
	0 5 T O R													

		INTAKE AIR TEMP. BY MODE 1	2	3	4	5	6	7	8	9	10	11	12	13
		d d d												
	0 6 T E													

		BLOWER INLET TEMP. BY MODE 1	2	3	4	5	6	7	8	9	10	11	12	13
		d d d												
	0 7 T B													

SOUTHWEST RESEARCH INSTITUTE

DEPARTMENT OF EMISSIONS RESEARCH

DIESEL PARTICULATE GRAVIMETRIC ANALYSIS

PROJECT 11-

ENCODED BY

DATE ENCODED

PAGE 2 OF 2

RUN NO.	SEQ	ORIFICE ΔP FOR HI-VOL SAMPLE BY MODE												
		1	2	3	4	5	6	7	8	9	10	11	12	13
d – d d d		d . d d												
–	0 8 D P Ø R													
		ENGINE FUEL RATE IN LB_m/HR BY MODE												
		1	2	3	4	5	6	7	8	9	10	11	12	13
		d d . d												
	0 9 F U E L													
		ENGINE AIRFLOW ORIFICE ΔP BY MODE												
		1	2	3	4	5	6	7	8	9	10	11	12	13
		d d . d d												
	1 0 D P E													
		DILUTE NO_x CONCENTRATION IN PPM BY MODE												
		1	2	3	4	5	6	7	8	9	10	11	12	13
		d d d . d												
	1 1 D N Ø X													
		RAW NO_x CONCENTRATION IN PPM BY MODE												
		1	2	3	4	5	6	7	8	9	10	11	12	13
		d d d d												
	1 2 R N Ø X													

```
SER,PERCC1.         DAN M, 2657
PERATE,P20,T20,PP100,PL20,CM50000.
ID          113718001     SRI1067       23RATECC301380001
RUN(S)
COPYCR(INPUT,OUTPUT)
LDSET(PRESET=ZERO)
MAP(OFF)
REDUCE.
LGO.
COPYCR(INPUT,OUTPUT)
-
      NOLIST
      PROGRAM RATECC(INPUT,OUTPUT,TAPE60=INPUT)
      DIMENSION TOR(13),DPE(13),TE(13),FUEL(13),RNOX(13),ANOX(13)
      DIMENSION TB(13),DPOR(13),TIME(13)
      DIMENSION EXH(13),AIR(13),FLOWOR(13)
      DIMENSION SAMP(4),ENGCODE(2),IFLTRS(5),GJ(5)
      EQUIVALENCE (GJ(1),G471),(GJ(2),G472),(GJ(3),G473),(GJ(4),G474)
      EQUIVALENCE (GJ(5),GERC)
C                                       INITIALIZE ARRAYS TO ZERO
  301  DO 1 I=1,13
        TOR(I)=DPE(I)=TE(I)=FUEL(I)=0
        RNOX(I)=DNOX(I)=TB(I)=DPOR(I)=TIME(I)=0
        EXH(I)=AIR(I)=FLOWOR(I)=0
    1  CONTINUE
C                                       READ HEADER CARD
      READ(60,100)JRUN,JSEQ,JDATE,JRPM,LOAD,IFLTRS,ENGCODE
      IF(EOF,60) 80, 2
    2 PRINT 200
      READ(60,101)KRUN,KSEQ,FUELC,G471,G472,G473,G474,GERC,PA,CB,TOTIME
     1         ,N
      PRINT 201,JRUN,JDATE,ENGCODE,FUELC,LOAD,JRPM
C                                       CHECK FOR FILTERS
      IS=1HS
      IERC=0
      IFCT=1
      IF(IFLTRS(2).NE.9H          ) GO TO 3
      IS=1H
      GO TO 5
    3 IFCT=2
      IF(IFLTRS(3).NE.9H          )IFCT=3
      IF(IFLTRS(4).NE.9H          )IFCT=4
      IF(IFLTRS(5).EQ.9H          )GO TO 5
      IERC=1
      IFCT=5
    5 PRINT 202,IS,(L,IFLTRS(L),L=1,IFCT)
C                                       IF IS=BLANK THEN THIS IS A 8X10
C                                       SAMPLING SYSTEM,
C                                       IF IERC=1 THEN THIS IS AN ERC
C                                       SYSTEM,
C                                       THERE SHOULD BE A PARTICULATE
C                                       VALUE FOR EACH FILTER SO LETS
C                                       GO,
      IF(IS,EQ.1H )GAR=G471
      PRINT 203,(GJ(L),L=1,IFCT)
      IF(IS,EQ,1H ) GO TO 6
      PRINT 204
    6 IF(KRUN,NE,JRUN,OR,KSEQ,NE,2     )GO TO 8
      READ(60,102)KRUN,KSEC,V11,V21,V12,V22,V13,V23,V14,V24
      IF(KRUN,NE,JRUN,OR,KSEQ,NE,3     )GO TO 8
      IF(IS.EQ,1H ) GO TO 306
      PRINT 205,V11,V21,TOTIME,PA
      PRINT 206,V12,V22
      PRINT 207,V13,V23
      PRINT 208,V14,V24,CB,N
      GO TO 7
  306 PRINT 218,TOTIME,PA,CB,N
C                                        READ REST OF DATA FOR ALL MODES
    7 READ(60,103)KRUN,KSEQ,(TIME(I),I=1,N)
      IF(KRUN.NE.JRUN.OR.KSEQ.NE.4) GO TO 8
      READ(60,104)KRUN,KSEQ,(TOR(I),I=1,N)
      IF(KRUN.NE.JRUN.OR.KSEQ.NE.5) GO TO 8
      READ(60,105)KRUN,KSEQ,(TE(I),I=1,N)
      IF(KRUN.NE.JRUN.OR.KSEQ.NE.6) GO TO 8
      READ(60,106)KRUN,KSEQ,(TB(I),I=1,N)
      IF(KRUN.NE.JRUN.OR.KSEQ.NE.7) GO TO 8
      READ(60,107)KRUN,KSEQ,(DPOR(I),I=1,N)
      IF(KRUN.NE.JRUN.OR.KSEQ.NE.8) GO TO 8
      READ(60,108)KRUN,KSEQ,(FUEL(I),I=1,N)
      IF(KRUN.NE.JRUN.OR.KSEQ.NE.9) GO TO 8
      READ(60,109)KRUN,KSEQ,(DPE(I),I=1,N)
      IF(KRUN.NE.JRUN.OR.KSEQ.NE.10)GO TO 8
      READ(60,110)KRUN,KSEQ,(DNOX(I),I=1,N)
      IF(KRUN.NE.JRUN.OR.KSEQ.NE.11)GO TO 8
      READ(60,111)KRUN,KSEQ,(RNOX(I),I=1,N)
      IF(KRUN.NE.JRUN.OR.KSEQ.NE.12)GO TO 8
C                                        IF IS=S THEN TOR AND DPOR ARE
C                                        BLANK
      IF(IS.EQ.1HS)  9,10
    8 PRINT 209,KRUN,KSEQ
      STOP 10
C                                        4X47 SAMPLE OUTPUT FORMAT
    9 PRINT 210
      PRINT 211,(TIME(I),DPE(I),TE(I),FUEL(I),RNOX(I),DNOX(I),TB(I)
     1          ,I=1,N)
      GO TO 11
   10 PRINT 212
      PRINT 217,(TIME(I),TOR(I),DPE(I),TE(I),FUEL(I),RNOX(I),DNOX(I)
     1          ,TB(I),DPOR(I),I=1,N)
C                                        CALCULATIONS COMMON TO ALL
C                                        SAMPLE TYPES
   11 R=CB/TOTIME
       DO 12 I=1,N
        AIR(I)=102.7*(DPE(I)*PA/(TE(I)+460.))**.4842
        EXH(I)=AIR(I)+FUEL(I)/60.
   12  CONTINUE
C                                        CALCULATIONS FOR HI-VOL
      IF(IS.EQ.1HS) GO TO 14
      SMEXTI=0.
      SMFLTN=0.
       DO 13 I=1,N
        FLOWOR(I)=4.21*(DPOR(I)*PA/(TOR(I)+460.))**.5
        SMEXTI=SMEXTI+EXH(I)*TIME(I)
        SMFLTN=SMFLTN+FLOWOR(I)*TIME(I)*DNOX(I)/RNOX(I)
   13  CONTINUE
      PER= 3600.*GAR*SMEXTI/TOTIME/SMFLTN
      PRM= PER/GAR
      PC= 1.586E+8*GAR/SMFLTN
      PCM=PC/GAR
      PRINT 213
      GO TO 19
C                                        ERC SYSTEM
   14 IF(IERC.NE.1)GO TO 16
      PER=9.68E+7*GERC/TOTIME
      PRM=PER/GERC
      SUMEXH=0.
       DO 15 I=1,N
        SUMEXH=SUMEXH+EXH(I)
   15  CONTINUE
      PC=4.263E+12*GERC*N/TOTIME/SUMEXH
      PCM=PC/GERC
      PRINT 214
      GO TO 19
C                                                   4 X 47 SYSTEM
   16 V=V21-V11
      IF(V.LT.0)V=V+100.
      SAMP(1)=.0753*V
      V=V22-V12
      IF(V.LT.0)V=V+100.
      SAMP(2)=.0767*V
      V=V23-V13
      IF(V.LT.0)V=V+100.
      SAMP(3)=.0759*V
      V=V24-V14
      IF(V.LT.0)V=V+100.
      SAMP(4)=.0755*V
      SMEXTI=0.
      SMTINO=0.
       DO 17 I=1,N
        SMEXTI=SMEXTI+EXH(I)*TIME(I)
        SMTINO=SMTINO+TIME(I)*DNOX(I)/RNOX(I)
   17  CONTINUE
      RATIO=SMEXTI/SMTINO * 60.
      PRINT 215
       DO 18 J=1,4
        PER= GJ(J)*RATIO/SAMP(J)
        PRM= PER/GJ(J)
        PC= 2.643E+6*GJ(J)*TOTIME/SMTINO/SAMP(J)
        PCM=PC/GJ(J)
        PRINT 216,PER,PRM,PC,PCM
   18  CONTINUE
      GO TO 20
   19 PRINT 216,PER,PRM,PC,PCM
      IF(IFLTRS(2) .NE. 9H         ) GO TO 16
      IF(IFLTRS(3) .NE. 9H         ) GO TO 16
      IF(IFLTRS(4) .NE. 9H         ) GO TO 16
   20 GO TO 301
   80 STOP 100
C                                                 INPUT FORMATS
  100 FORMAT(A5,I2,A8,A4,A3,5A9,A10,A3)
  101 FORMAT(A5,I2,A6,5F8.6,F5.2,F6.0,F6.1,8X,I2)
  102 FORMAT(A5,I2,8F7.3)
  103 FORMAT(A5,I2,5X,13F4.0)
  104 FORMAT(A5,I2,5X,13F4.0)
  105 FORMAT(A5,I2,5X,13F4.0)
  106 FORMAT(A5,I2,5X,13F4.0)
  107 FORMAT(A5,I2,5X,13F4.2)
  108 FORMAT(A5,I2,5X,13F4.1)
  109 FORMAT(A5,I2,4X,13F5.2)
  110 FORMAT(A5,I2,4X,13F5.1)
  111 FORMAT(A5,I2,4X,13F5.0)
C                                                OUTPUT FORMATS
  200 FORMAT(*1        TABLE          PARTICULATE EMISSION RATE AND CONCEN
     1TRATION CALCULATIONS* )
  201 FORMAT(30X,*RUN *,A5,2X,A8 /15X,*ENGINE *,A10,A3,*  FUEL *,A6,
     1        *  LOAD *,A3,*  RPM *,A4 )
```

```
202 FORMAT(*0       FILTER*,A1,I2,1X,A9,4(I3,1X,A9))
203 FORMAT(*0       PARTICLES*,F10.6,4F13.6)
204 FORMAT(*0       DRY GAS METER READINGS  INITIAL   FINAL     TOTAL T
   1IME   ATM PRESSURE*)
                                              1*,F8.3,F9.3,F14.1,F13.2)
205 FORMAT(*
                                              2*,F8.3,F9.3)
206 FORMAT(*
                                              3*,F8.3,F9.3,    *    BLOWER
207 FORMAT(*
   1COUNT  NO. OF MODES*)
                                              4*,F8.3,F9.3,F15.0,I10)
208 FORMAT(*
209 FORMAT(* CARD OUT OF SEQUENCE *,A5,I3)
                            TIME    DPE    TE   FUEL     RNOX     DNOX
210 FORMAT(*0
   1 TB*)
                          *,F4.0,F8.2, F6.0, F7.1,  F9.1,    F9.1,
211 FORMAT(*
   1F6.0 )
                    TIME    TOR     DPE    TE   FUEL     RNOX     DNOX
212 FORMAT(*0
   1 TB   DPOR*)
                    *,F4.0,F7.0,F7.2,F6.0, F7.1, F9.1,F9.1,F6.0,F7.2)
217 FORMAT(*
213 FORMAT(*0       HI-VOL*)
214 FORMAT(*0       E R C   SYSTEM*)
215 FORMAT(*0       4 X 47  SYSTEM*)
                          PARTICULATE EMISSION RATE =* ,F12.2/
216 FORMAT(*0
                                      MULTIPLIER    =* ,F10.0/
   1        *
                          PARTICULATE CONCENTRATION =* ,F10.0/
   2        *
                                      MULTIPLIER    =* ,F10.0 )
   3        *
                    TOTAL TIME   ATM PRESSURE   BLOWER COUNT   NO. OF M
218 FORMAT(*0
   1ODES*/          F17.1     ,F15.2          ,F15.0          ,I12)
    END
-
-
PM DAYFILE NEXT
-
PM USE REVERSE SIDE OF 1-PART PAPER
-
-
```

```
 TABLE          PARTICULATE EMISSION RATE AND CONCENTRATION CALCULATIONS
                             RUN 8-391  02/21/75
        ENGINE CUMS. NTC-290  FUEL EM224F  LOAD 100  RPM 2100

FILTERS 1 FP47-395   2  A47-621   3  A47-622   4  A47-623   5 FP47-422

PARTICLES   .002474      .002476      .002442      .002498      .001139

DRY GAS METER READINGS  INITIAL   FINAL      TOTAL TIME   ATM PRESSURE
                      1  99.174   17.673        2400.1         29.38
                      2  35.198   53.835
                      3  76.527   95.075     BLOWER COUNT  NO. OF MODES
                      4  90.365    9.584         65687         10

      TIME     DPE     TE   FUEL     RNOX      DNOX    TB
      240     3.80     74  114.0   1797.0      92.6   116
      240     3.80     80  114.0   1797.0     108.1   123
      240     3.80     86  114.0   1814.0     108.3   127
      240     3.60     75  114.0   1832.0     107.0   127
      240     3.80     79  113.0   1849.0     109.0   127
      240     3.80     79  113.0   1901.0     107.0   125
      240     3.80     73  113.0   1884.0     106.3   127
      240     3.80     72  113.0   1904.0     100.7   125
      240     3.80     76  113.0   1884.0     103.5   125
      240     3.80     80  113.0   1908.0     104.2   125

E R C   SYSTEM

        PARTICULATE EMISSION RATE =        45.94
                    MULTIPLIER    =      40332
        PARTICULATE CONCENTRATION =      40560
                    MULTIPLIER    =   35610552

4 X 47  SYSTEM

        PARTICULATE EMISSION RATE =        94.26
                    MULTIPLIER    =      38100
        PARTICULATE CONCENTRATION =      83249
                    MULTIPLIER    =   33649356

        PARTICULATE EMISSION RATE =        91.93
                    MULTIPLIER    =      37127
        PARTICULATE CONCENTRATION =      81189
                    MULTIPLIER    =   32790543

        PARTICULATE EMISSION RATE =        92.06
                    MULTIPLIER    =      37699
        PARTICULATE CONCENTRATION =      81307
                    MULTIPLIER    =   33295161

        PARTICULATE EMISSION RATE =        91.36
                    MULTIPLIER    =      36575
        PARTICULATE CONCENTRATION =      80693
                    MULTIPLIER    =   32302954
```

```
TABLE         PARTICULATE EMISSION RATE AND CONCENTRATION CALCULATIONS
                        RUN 6-377  02/19/75
      ENGINE CUMS. NTC-290  FUEL EM224F  LOAD 100  RPM 2100

FILTER  1   AR-223

PARTICLES   .132100

TOTAL TIME   ATM PRESSURE   BLOWER COUNT   NO. OF MODES
    2399.7          29.29          65705            10

TIME    TOR     DPE      TE   FUEL      RNOX       DNOX     TB    DPOR
240     105     3.30     80  116.0     1842.0     146.5    133    3.30
240     113     3.60     79  112.0     1980.0     125.3    131    3.30
240     118     3.60     81  112.0     2004.0     125.9    119    3.30
240     124     3.60     80  112.0     2022.0     117.7    131    3.30
240     127     3.60     80  112.0     2032.0     118.4    131    3.30
240     135     3.60     81  112.0     2015.0     115.2    129    3.30
240     140     3.60     81  112.0     1994.0     113.9    131    3.30
240     145     3.60     79  112.0     2004.0     109.7    131    3.30
240     148     3.60     79  112.0     1980.0     111.1    130    2.90
240     150     3.60     70  112.0     2032.0     114.3    130    2.55

HI-VOL

        PARTICULATE EMISSION RATE =          94.49 g/hr
                    MULTIPLIER    =           715 hr^-1
        PARTICULATE CONCENTRATION =        86251 µg/m^3
                    MULTIPLIER    =       652920 m^-3 (10^6)
```

APPENDIX D

SMOKE AND GASEOUS EMISSIONS DATA

TABLE D-1. RESULTS OF FEDERAL SMOKE TESTS ON A DETROIT DIESEL 6L71-T ENGINE USING SEVERAL FUELS

Fuel codes	Fuel type	% opacity by PHS smokemeter		
		"A" factor	"B" factor	"C" factor
"A" or EM-197-F	No. 1 Kerosene	11.2	2.1	18.0
		12.5	2.1	19.5
		16.7	4.8	22.6
		16.7	5.4	21.4
	Averages	14.3	3.6	20.4
"B" or EM-195-F	No. 2 Emissions test fuel	11.9	1.4	20.6
		12.8	2.1	20.8
		13.0	1.9	21.8
		13.2	2.4	19.9
		13.6	1.9	20.8
		11.2	1.8	15.6
		10.1	1.5	14.3
	Averages	12.3	1.9	19.1
"C" or EM-193-F	"No. 1-1/2" Special blend	19.2	2.3	28.7
		17.9	2.8	26.5
		18.5	2.8	26.9
		10.5	1.9	14.6
		10.2	1.7	14.3
	Averages	15.3	2.3	22.2
"A + additive" or EM-206-F	No. 1 + Ethyl DII-2	14.8	2.7	23.6
		15.0	2.5	24.6
		16.6	4.7	21.2
		15.7	4.1	20.7
	Averages	15.5	3.5	22.5
"B + additive" or EM-207-F	No. 2 + Lubrizol 8005	3.5	1.0	5.7
		3.0	0.9	4.6
	Averages	3.2	1.0	5.2
"C + additive" or EM-208-F	"No. 1-1/2" + Lubrizol 8005	9.9	1.8	14.8
		10.8	1.8	16.3
		6.2	1.0	8.9
		5.1	1.0	7.2
	Averages	8.0	1.4	11.8

TABLE D-2. RESULTS OF FEDERAL SMOKE TESTS ON A CUMMINS NTC-290 ENGINE USING SEVERAL FUELS

Fuel codes	Fuel type	% opacity by PHS smokemeter		
		"A" factor	"B" factor	"C" factor
"A" or EM-197F	No. 1 Kerosene	7.3	4.4	11.4
		6.8	4.2	10.1
	Averages	7.1	4.3	10.8
"A + DII-2" or EM-209-F	No. 2 Emissions test fuel	5.2	3.6	7.2
		4.5	3.7	6.7
	Averages	4.9	3.7	7.0
"B" or EM-204-F	"No. 1-1/2" Special blend	7.5	4.1	10.3
		7.8	4.0	10.4
		7.0	3.8	9.9
		8.7	4.4	11.8
		8.8	3.8	12.8
		7.9	4.3	11.9
		7.5	4.6	11.2
		7.5	4.7	10.4
		7.3	4.2	10.1
		7.9	3.8	12.3
	Averages	7.8	4.2	11.1
"B + 8005" or EM-224-F	No. 1 + Ethyl DII-2	2.5	1.5	3.8
		2.5	1.2	4.4
	Averages	2.5	1.4	4.1
"C" or EM-198-F	No. 2 + Lubrizol 8005	8.2	4.4	10.6
		7.6	4.5	10.0
	Averages	7.9	4.5	10.3
"C + 8005" or EM-211-F	"No. 1-1/2" + Lubrizol 8005	4.5	2.0	7.1
		3.0	1.1	5.1
	Averages	3.8	1.6	6.1

TABLE D-3. GASEOUS EMISSIONS FROM A DETROIT DIESEL 6L71-T ENGINE OPERATED ON THE 13-MODE PROCEDURE

Fuel codes	Fuel type	Cycle comp. emis., g/hp hr			
		HC	CO	NO_x	$HC+NO_x$
"A" or EM-197-F	No. 1 Kerosene	0.97	2.19	11.6	12.6
		0.94	2.22	12.0	13.0
	Averages	0.96	2.20	11.8	12.8
"B" or EM-195-F	No. 2 Emissions test fuel	0.49[a]	2.66	11.6	12.1
		0.44[a]	2.33	11.7	12.2
		0.58[a]	2.10	12.6	13.1
		0.81	2.80	13.0	13.8
		0.84	2.53	13.1	13.9
		0.89	2.33	12.9	13.8
	Averages	0.68	2.46	12.5	13.2
"C" or EM-198-F	"No. 1-1/2" Special blend	0.91	2.28	11.3	12.3
		0.97	2.37	11.4	12.3
		1.11	2.34	11.4	12.5
	Averages	1.00	2.33	11.4	12.4
"A + additive" or EM-206-F	No. 1 Kerosene + Ethyl DII-2	1.12	2.35	10.3	11.4
		1.12	2.10	10.6	11.7
	Averages	1.12	2.22	10.4	11.6
"B + additive" or EM-207-F	No. 2 + Lubrizol 8005	1.12	3.07	11.3	12.4
		1.25	3.22	11.2	12.4
	Averages	1.18	3.14	11.2	12.4
"C + additive" or EM-208-F	"No. 1-1/2" + Lubrizol 8005	1.21	2.85	11.8	13.0
		1.43	3.18	11.2	12.7
	Averages	1.32	3.02	11.5	12.8

[a] Runs conducted January 1974, all others September and October 1974

TABLE D-4. GASEOUS EMISSIONS FROM A CUMMINS NTC-290 ENGINE OPERATED ON THE 13-MODE PROCEDURE

Fuel codes	Fuel type	Cycle comp. emis., g/hp hr			
		HC	CO	NO_x	$HC+NO_x$
"A" or EM-197-F	No. 1 Kerosene	0.31	2.43	12.1	12.4
		0.30	2.57	11.9	12.2
	Averages	0.31	2.50	12.0	12.3
"A + DII-2" or EM-209-F	No. 2 Emissions test fuel	0.26	2.49	11.7	12.0
		0.25	2.44	12.5	12.7
	Averages	0.26	2.47	12.1	12.4
"B" or EM-204-F	"No. 1-1/2" Special blend	0.29	2.46	12.6	12.9
		0.36	2.53	12.1	12.5
		0.34	2.31	12.6	12.9
		0.35	2.24	11.6	11.9
		0.31	2.49	12.7	13.0
		0.32	2.32	12.8	13.1
		0.32	2.68	12.6	12.9
		0.33	2.63	12.5	12.8
		0.31	2.47	12.4	12.8
		0.35	2.49	11.9	12.2
		0.33	2.66	12.0	12.3
		0.44	2.81	12.4	12.8
		0.33	2.65	12.4	12.7
		0.33	2.57	13.7	14.1
	Averages	0.34	2.52	12.5	12.8
"B + 8005" or EM-224-F	No. 1 Kerosene + Ethyl DII-2	0.41	2.96	12.1	12.5
		0.38	2.62	12.9	13.3
	Averages	0.40	2.79	12.5	12.9
"C" or EM-198-F	No. 2 + Lubrizol 8005	0.29	2.29	11.3	11.6
		0.28	2.41	13.4	13.7
	Averages	0.29	2.35	12.4	12.7
"C + 8005" or EM-211-F	"No. 1-1/2" + Lubrizol 8005	0.34	2.72	12.8	13.2
		0.39	2.89	12.3	12.7
		0.34	3.17	12.6	13.0
	Averages	0.36	2.93	12.6	13.0

APPENDIX E

AVERAGE MASS RATE AND CONCENTRATION RESULTS

TABLE E-1. MASS RATE RESULTS OF PARTICULATE SAMPLING ON DETROIT DIESEL 6L71-T ENGINE

Dilution Tunnel, 47mm Glass Fiber Filters

	Grams particulate per hour by fuel					
Operating condition	A	B	C	A+additive[a]	B+additive[b]	C+additive[b]
Idle	5.3	9.2	5.1	2.5	1.4	5.9
1600 rpm - 0% load	26.	36.	25.	27.	48.	67.
1600 rpm - 25% load	33.	49.	41.	36.	169.	183.
1600 rpm - 50% load	49.	72.	59.	54.	333.	136.
1600 rpm - 75% load	67.	111.	72.	64.	145.	104.
1600 rpm - 100% load	65.	77.	65.	59.	155.	100.
2100 rpm - 0% load	47.	56.	43.	45.	147.	67.
2100 rpm - 25% load	55.	62.	51.	52.	465.	116.
2100 rpm - 50% load	78.	94.	87.	90.	300.	138.
2100 rpm - 75% load	84.	114.	94.	91.	247.	176.
2100 rpm - 100% load	107.	137.	84.	105.	198.	142.
Composite	64.	71.	65.	67.	144.	73.

Dilution Tunnel, 47mm Fluoropore Filters

	Grams particulate per hour by fuel					
Operating condition	A	B	C	A+additive[a]	B+additive[b]	C+additive[b]
Idle	9.1	13.	8.1	9.3	1.6	6.0
1600 rpm - 0% load	29.	42.	24.	30.	42.	67.
1600 rpm - 25% load	36.	64.	55.	45.	103.	197.
1600 rpm - 50% load	56.	54.	114.	72.	355.	155.
1600 rpm - 75% load	68.	-----	100.	84.	146.	106.
1600 rpm - 100% load	69.	-----	78.	70.	161.	105.
2100 rpm - 0% load	64.	-----	116.	57.	144.	80.
2100 rpm - 25% load	56.	-----	64.	71.	464.	135.
2100 rpm - 50% load	137.	83.	99.	111.	307.	154.
2100 rpm - 75% load	136.	-----	169.	123.	252.	179.
2100 rpm - 100% load	203.	150.	138.	122.	203.	146.
Composite	60.	-----	86.	79.	149.	81.

[a] Primary hexyl nitrate (cetane improver)
[b] Organo-metallic (smoke suppressant)

TABLE E-1 (Cont'd). MASS RATE RESULTS OF PARTICULATE SAMPLING ON DETROIT DIESEL 6L71-T ENGINE

Dilution Tunnel, 8 x 10 Glass Fiber Filters

	Grams particulate per hour by fuel					
Operating condition	A	B	C	A+additive[a]	B+additive[b]	C+additive[b]
Idle	3.3	9.8	5.5	4.3	21.	5.6
1600 rpm - 0% load	32.	42.	40.	29.	-----	56.
1600 rpm - 25% load	-----	48.	56.	-----	-----	-----
1600 rpm - 50% load	63.	81.	67.	62.	71.	74.
1600 rpm - 75% load	-----	87.	74.	-----	-----	-----
1600 rpm - 100% load	79.	92.	73.	71.	73.	72.
2100 rpm - 0% load	51.	70.	59.	50.	-----	118.
2100 rpm - 25% load	-----	69.	49.	-----	-----	-----
2100 rpm - 50% load	83.	114.	107.	86.	155.	162.
2100 rpm - 75% load	-----	112.	117.	-----	-----	-----
2100 rpm - 100% load	104.	150.	102.	87.	161.	191.
Composite	82.	92.	76.	76.	148.	104.

ERC Sampler, 47mm Fluoropore Filters

	Grams particulate per hour by fuel					
Operating condition	A	B	C	A+additive[a]	B+additive[b]	C+additive[b]
Idle		11.	118.	9.8	10.	12.
1600 rpm - 0% load	21.	42.	38.	15.	42.	10.
1600 rpm - 25% load	-----	122.	47.	31.	77.	20.
1600 rpm - 50% load	42.	162.	56.	36.	193.	37.
1600 rpm - 75% load	-----	-----	192.	57.	82.	42.
1600 rpm - 100% load	92.	-----	-----	73.	85.	140.
2100 rpm - 0% load	28.	-----	33.	20.	45.	19.
2100 rpm - 25% load	-----	-----	32.	40.	210.	49.
2100 rpm - 50% load	39.	-----	42.	39.	151.	102.
2100 rpm - 75% load	-----	-----	83.	76.	112.	106.
2100 rpm - 100% load	108.	-----	105.	66.	79.	77.
Composite	-----	-----	-----	-----	-----	-----

[a] Primary hexyl nitrate (cetane improver)

[b] Organo-metallic (smoke suppressant)

TABLE E-1 (Cont'd.) MASS RATE RESULTS OF PARTICULATE SAMPLING ON DETROIT DIESEL 6L-71T ENGINE

Dilution Tunnel, 293mm Fluoropore Filters

	Grams particulate per hour by fuel					
Operating condition	A	B	C	A + additive[a]	B + additive[b]	C + additive[b]
Idle	6.90	11.2				
1600 rpm - 0% load	-----	33.4				
1600 rpm - 25% load	-----	-----				
1600 rpm - 50% load	57.1	66.6				
1600 rpm - 75% load	-----	-----				
1600 rpm - 100% load	-----	128.				
2100 rpm - 0% load	-----	53.3				
2100 rpm - 25% load	-----	-----				
2100 rpm - 50% load	-----	102.				
2100 rpm - 75% load	-----	-----				
2100 rpm - 100% load	89.8	128.				
Composite	51.8	60.4				

TABLE E-2. CONCENTRATION RESULTS OF PARTICULATE SAMPLING ON DETROIT DIESEL 6L-71T ENGINE

Dilution Tunnel, 47mm Glass Fiber Filters

	Milligrams particulate per standard cubic meter					
Operating condition	A	B	C	A + additive[a]	B + additive[b]	C + additive[b]
Idle	22.	41.	12.	11.	5.6	25.
1600 rpm - 0% load	33.	46.	31.	34.	52.	81.
1600 rpm - 25% load	38.	57.	48.	43.	197.	206.
1600 rpm - 50% load	54.	77.	63.	57.	349.	139.
1600 rpm - 75% load	67.	106.	70.	63.	135.	99.
1600 rpm - 100% load	58.	65.	56.	52.	129.	85.
2100 rpm - 0% load	43.	52.	39.	41.	131.	60.
2100 rpm - 25% load	46.	52.	43.	44.	372.	96.
2100 rpm - 50% load	60.	71.	99.	69.	216.	102.
2100 rpm - 75% load	58.	77.	65.	63.	164.	117.
2100 rpm - 100% load	69.	83.	52.	68.	122.	89.
Composite	59.	65.	59.	61.	129.	67.

[a] Primary hexyl nitrate (cetane improver)

[b] Organo-metallic (smoke suppressant)

TABLE E-2. (Cont'd). CONCENTRATION RESULTS OF PARTICULATE SAMPLING ON DETROIT DIESEL 6L-71T ENGINE

Dilution Tunnel, 47mm Fluoropore Filters

Operating condition	Milligrams particulate per standard cubic meter					
	A	B	C	A + additive[a]	B + additive[b]	C + additive[b]
Idle	38.	56.	18.	40.	7.1	25.
1600 rpm - 0% load	37.	53.	31.	37.	53.	81.
1600 rpm - 25% load	42.	75.	64.	53.	118.	221.
1600 rpm - 50% load	60.	58.	124.	76.	573.	158.
1600 rpm - 75% load	67.	-----	96.	82	137.	100.
1600 rpm - 100% load	62	-----	67.	62.	134.	90.
2100 rpm - 0% load	58.	-----	59.	52.	129.	71
2100 rpm - 25% load	46.	-----	53.	59.	371.	111.
2100 rpm - 50% load	105.	63.	75.	85.	221.	115.
2100 rpm - 75% load	94.	-----	116.	85.	165.	119.
2100 rpm - 100% load	129.	93.	85.	78.	124.	91.
Composite	68.	-----	90.	82.	134.	73.

Dilution Tunnel, 8 x 10 Glass Fiber Filters

Operating condition	Milligrams particulate per standard cubic meter					
	A	B	C	A + additive[a]	B + additive[b]	C + additive[b]
Idle	19.	47.	30.	20.	101.	30.
1600 rpm - 0% load	40.	55.	52.	36.	-----	72.
1600 rpm - 25% load	-----	62.	66.	-----	-----	-----
1600 rpm - 50% load	69.	91.	74.	67.	76.	80.
1600 rpm - 75% load	-----	88.	74.	-----	-----	-----
1600 rpm - 100% load	71.	73.	64.	65.	64.	63.
2100 rpm - 0% load	47.	64.	55.	46.	-----	107.
2100 rpm - 25% load	-----	61.	41.	-----	-----	-----
2100 rpm - 50% load	63.	90.	82.	67.	117.	122.
2100 rpm - 75% load	------	80.	82.	-----	-----	-----
2100 rpm - 100% load	66.	94.	64.	56.	99.	120.
Composite	67.	83.	72.	69.	132.	94.

[a] Primary hexyl nitrate (cetane improver)
[b] Organo-metallic (smoke suppressant)

TABLE E-2 (Cont'd). CONCENTRATION RESULTS OF PARTICULATE SAMPLING ON DETROIT DIESEL 6L-71T ENGINE

ERC Sampler, 47mm Fluoropore Filters

Operating condition	Milligrams particulate per standard cubic meter					
	A	B	C	A + additive[a]	B + additive[b]	C + additive[b]
Idle	5.9	10.	44.	31.	41.	33.
1600 rpm - 0% load	27.	53.	47.	19.	53.	12.
1600 rpm - 25% load	-----	143.	54.	36.	89.	21.
1600 rpm - 50% load	46.	174.	60.	38.	202.	37.
1600 rpm - 75% load	-----	----	185.	56.	69.	40.
1600 rpm - 100% load	82.	-----	58.	65.	58.	112.
2100 rpm - 0% load	25.	-----	30.	18.	40.	16.
2100 rpm - 25% load	-----	-----	27.	34.	168.	36.
2100 rpm - 50% load	30.	-----	32.	30.	96.	66.
2100 rpm - 75% load	-----	-----	57.	53.	64.	62.
2100 rpm - 100% load	70.	-----	66.	43.	37.	63.
Composite	-----	-----	-----	-----	-----	-----

Dilution Tunnel, 293mm Fluoropore Filters

Operating Condition	Milligrams particulate per standard cubic meter					
	A	B	C	A + additive[a]	B + additive[b]	C + additive[b]
Idle	14.	22.				
1600 rpm - 0% load	-----	42.				
1600 rpm - 25% load	-----	-----				
1600 rpm - 50% load	63.	73.				
1600 rpm - 75% load	-----	-----				
1600 rpm - 100% load	-----	113.				
2100 rpm - 0% load	-----	48.				
2100 rpm - 25% load	-----	-----				
2100 rpm - 50% load	-----	77.				
2100 rpm - 75% load	-----	-----				
2100 rpm - 100% load	59.	81.				
Composite	49.	64.				

[a] Primary hexyl nitrate (cetane improver)

[b] Organo-metallic (smoke suppressant)

TABLE E-3. MASS RATE RESULTS OF PARTICULATE SAMPLING ON CUMMINS NTC-290 ENGINE

Dilution Tunnel, 47mm Glass Fiber Filters

Operating condition	Grams particulate per hour by fuel					
	A	B	C	A + additive[a]	B + additive[b]	C + additive[b]
Idle	0.78	3.8	1.9	0.60	5.0	3.5
1500 rpm - 0% load	6.6	12.	9.	7.5	20.	14.
1500 rpm - 25% load	15.	25.	18.	16.	31.	28.
1500 rpm - 50% load	19.	37.	27.	20.	48.	40.
1500 rpm - 75% load	24.	37.	24.	22.	56.	49.
1500 rpm - 100% load	22.	42.	26.	22.	73.	53.
2100 rpm - 0% load	15.	26.	23.	19.	35.	29.
2100 rpm - 25% load	38.	65.	46.	38.	79.	59.
2100 rpm - 50% load	40.	64.	50.	32.	65.	54.
2100 rpm - 75% load	39.	68.	42.	37.	79.	66.
2100 rpm - 100% load	46.	69.	52.	52.	92.	74.
Composite	20.	35.	26.	20.	44.	29.

Dilution Tunnel, 47mm Fluoropore Filters

Operating condition	Grams particulate per hour by fuel					
	A	B	C	A + additive[a]	B + additive[b]	C + additive[b]
Idle	0.82	4.1	2.6	0.76	5.3	2.9
1500 rpm - 0% load	7.7	12.	9.1	7.4	21.	15.
1500 rpm - 25% load	17.	28.	18.	16.	31.	28.
1500 rpm - 50% load	18.	40.	28.	21.	46.	40.
1500 rpm - 75% load	21.	38.	24.	22.	55.	50.
1500 rpm - 100% load	24.	45.	24.	20.	75.	44.
2100 rpm - 0% load	24.	24.	23.	19.	37.	30.
2100 rpm - 25% load	37.	68.	48.	37.	79.	60.
2100 rpm - 50% load	43.	66.	48.	34.	67.	55.
2100 rpm - 75% load	41.	70.	42.	38.	80.	53.
2100 rpm - 100% load	50.	70.	46.	54.	94.	76.
Composite	26.	37.	29.	22.	50.	40.

[a] Primary hexyl nitrate (cetane improver)

[b] Organo-metallic (smoke suppressant)

TABLE E-3 (Cont'd.) MASS RATE RESULTS OF PARTICULATE SAMPLING ON CUMMINS NTC-290 ENGINE

Dilution Tunnel, 8 x 10 Glass Fiber Filters

	Grams particulate per hour by fuel					
Operating condition	A	B	C	A + additive[a]	B + additive[b]	C + additive[b]
Idle	1.7	5.3	3.6	2.2	5.7	3.3
1500 rpm - 0% load	10.	17.	16.	13.	19.	17.
1500 rpm - 25% load	23.	30.	27.	20.	35.	28.
1500 rpm - 50% load	29.	46.	28.	23.	48.	38.
1500 rpm - 75% load	25.	45.	29.	22.	56.	47.
1500 rpm - 100% load	32.	55.	34.	28.	69.	52.
2100 rpm - 0% load	25.	32.	34.	26.	38.	34.
2100 rpm - 25% load	48.	43.	54.	48.	55.	51.
2100 rpm - 50% load	50.	56.	59.	47.	70.	59.
2100 rpm - 75% load	44.	74.	46.	38.	83.	65.
2100 rpm - 100% load	52.	85.	56.	48.	94.	90.
Composite	32.	47.	33.	29.	51.	40

ERC Sampler, 47mm Fluoropore Filters

	Grams particulate per hour by fuel					
Operating condition	A	B	C	A + additive[a]	B + additive[b]	C + additive[b]
Idle	1.9	3.1	4.5	2.6	0.83	0.58
1500 rpm - 0% load	5.5	4.8	4.8	1.4	6.9	7.6
1500 rpm - 25% load	-----	8.9	-----	-----	-----	-----
1500 rpm - 50% load	13.	24.	9.6	8.8	22.	17.
1500 rpm - 75% load	-----	-----	-----	-----	-----	-----
1500 rpm - 100% load	9.8	35.	7.8	8.8	25.	19.
2100 rpm - 0% load	7.7	12.	11.	11.	14.	21.
2100 rpm - 25% load	-----	-----	-----	-----	-----	-----
2100 rpm - 50% load	18.	35.	25.	16.	33.	41.
2100 rpm - 75% load	-----	-----	-----	-----	-----	----
2100 rpm - 100% load	22.	54.	33.	21.	46.	48.
Composite	-----	-----	-----	-----	-----	-----

[a] Primary hexyl nitrate (cetane improver)

[b] Organo-metallic (smoke suppressant)

TABLE E-3 (Cont'd.) MASS RATE RESULTS OF PARTICULATE SAMPLING ON CUMMINS NTC-290 ENGINE

Dilution Tunnel, 293mm Fluoropore Filters

	Grams particulate per hour by fuel					
Operating condition	A	B	C	A + additive[a]	B + additive[b]	C + additive[b]
Idle		3.9	1.7	1.1		
1500 rpm - 0% load		15.	-----	-----		
1500 rpm - 25% load		-----	-----	-----		
1500 rpm - 50% load		37.	27.	21.		
1500 rpm - 75% load		-----	-----	-----		
1500 rpm - 100% load		44.	31.	27.		
2100 rpm - 0% load		-----	-----	-----		
2100 rpm - 25% load		-----	-----	-----		
2100 rpm - 50% load		63.	-----	-----		
2100 rpm - 75% load		-----	-----	-----		
2100 rpm - 100% load		64.	51.	49.		
Composite		34.	32.	24.		

TABLE E-4. CONCENTRATION RESULTS OF PARTICULATE SAMPLING ON CUMMINS NTC-290 ENGINE

Dilution Tunnel, 47mm Glass Fiber Filters

	Milligrams particulate per standard cubic meter					
Operating condition	A	B	C	A + additive[a]	B + additive[b]	C + additive[b]
Idle	3.5	17.	8.1	2.5	23.	15.
1500 rpm - 0% load	12.	23.	17.	14.	37.	26.
1500 rpm - 25% load	27.	43.	33.	28.	55.	48.
1500 rpm - 50% load	30.	60.	44.	33.	77.	64.
1500 rpm - 75% load	37.	54.	35.	34.	86.	72.
1500 rpm - 100% load	29.	55.	34.	29.	95.	70.
2100 rpm - 0% load	21.	35.	32.	27.	48.	40.
2100 rpm - 25% load	47.	74.	57.	48.	98.	72.
2100 rpm - 50% load	45.	70.	54.	36.	73.	59.
2100 rpm - 75% load	41.	68.	42.	39.	79.	67.
2100 rpm - 100% load	41.	61.	47.	48.	81.	67.
Composite	28.	48.	36.	27.	61.	39.

[a] Primary hexyl nitrate (cetane improver)

[b] Organo-metallic (smoke suppressant)

TABLE E-4 (Cont'd.) CONCENTRATION RESULTS OF PARTICULATE SAMPLING ON CUMMINS NTC-290 ENGINE

Dilution Tunnel, 47mm Fluoropore Filters

Operating condition	Milligrams particulate per standard cubic meter					
	A	B	C	A + additive[a]	B + additive[b]	C + additive[b]
Idle	3.7	18.	11.	3.2	24.	13.
1500 rpm - 0% load	14.	22.	17.	13.	39.	28.
1500 rpm - 25% load	30.	48.	32.	29.	55.	49.
1500 rpm - 50% load	30.	64.	46.	34.	74.	65.
1500 rpm - 75% load	32.	55.	36.	33.	84.	74.
1500 rpm - 100% load	32.	59.	31.	27.	98.	58.
2100 rpm - 0% load	32.	33.	32.	27.	51.	41.
2100 rpm - 25% load	46.	77.	60.	46.	97.	75.
2100 rpm - 50% load	48.	72.	52.	38.	75.	61.
2100 rpm - 75% load	43.	70.	42.	40.	80.	54.
2100 rpm - 100% load	45.	62.	41.	50.	83.	69.
Composite	36.	51.	39.	31.	69.	55.

Dilution Tunnel, 8 x 10 Glass Fiber Filters

Operating condition	Milligrams particulate per standard cubic meter					
	A	B	C	A + additive[a]	B + additive[b]	C + additive[b]
Idle	7.5	24.	15.	9.5	26.	15.
1500 rpm - 0% load	19.	33.	29.	24.	36.	32.
1500 rpm - 25% load	41.	54.	48.	35.	62.	49.
1500 rpm - 50% load	47.	75.	46.	37.	78.	61.
1500 rpm - 75% load	37.	67.	42.	33.	83.	67.
1500 rpm - 100% load	44.	74.	45.	38.	92.	75.
2100 rpm - 0% load	35.	45.	46.	35.	53.	47.
2100 rpm - 25% load	60.	54.	67.	59.	68.	63.
2100 rpm - 50% load	57.	64.	64.	54.	79.	66.
2100 rpm - 75% load	45.	76.	47.	39.	84.	64.
2100 rpm - 100% load	47.	77.	49.	44.	86.	66.
Composite	45.	66.	45.	40.	71.	54.

[a] Primary hexyl nitrate (cetane improver)

[b] Organo-metallic (smoke suppressant)

TABLE E-4 (Cont'd). CONCENTRATION RESULTS OF PARTICULATE SAMPLING ON CUMMINS NTC-290 ENGINE

ERC Sampler, 47mm Fluoropore Filters

Operating condition	Milligrams particulate per standard cubic meter					
	A	B	C	A + additive[a]	B + additive[b]	C + additive[b]
Idle	8.0	14.	19.	11.	3.7	2.5
1500 rpm - 0% load	10.	9.	8.7	2.5	13.	14.
1500 rpm - 25% load	-----	15.	-----	-----	-----	-----
1500 rpm - 50% load	21.	39.	16.	14.	35.	27.
1500 rpm - 75% load	-----	-----	-----	-----	-----	-----
1500 rpm - 100% load	13.	46.	10.	12.	32.	25.
2100 rpm - 0% load	11.	17.	15.	15.	20.	28.
2100 rpm - 25% load	-----	-----	-----	-----	-----	-----
2100 rpm - 50% load	20.	38.	27.	19.	36.	45.
2100 rpm - 75% load	-----	-----	-----	-----	-----	-----
2100 rpm - 100% load	20.	48.	29.	19.	41.	44.
Composite	-----	-----	-----	-----	-----	-----

Dilution Tunnel, 293mm Fluoropore Filters

Operating condition	Milligrams particulate per standard cubic meter					
	A	B	C	A + additive[a]	B + additive[b]	C + additive[b]
Idle		18.	7.3	4.7		
1500 rpm - 0% load		28.	-----	-----		
1500 rpm - 25% load		-----	-----	-----		
1500 rpm - 50% load		59.	45.	34.		
1500 rpm - 75% load		-----	-----	-----		
1500 rpm - 100% load		58.	42.	36.		
2100 rpm - 0% load		-----	-----	-----		
2100 rpm - 25% load		-----	-----	-----		
2100 rpm - 50% load		71.	-----	-----		
2100 rpm - 75% load		-----	-----	-----		
2100 rpm - 100% load		58.	45.	37.		
Composite		47.	43.	33.		

[a] Primary hexyl nitrate (cetane improver)
[b] Organo-metallic (smoke suppressant)

APPENDIX F

TRACE METALS IN PARTICULATE

TABLE F-1. ANALYSIS FOR METALS IN PARTICULATE SAMPLES FROM FOUR FUELS, DETROIT DIESEL 6L71-T ENGINE

Fuel	Operating condition	Metal analysis in $\mu g/cm^2$ on filter									
		Ca	V	Mn	Ni	Cu	Zn	Pb	Sr	Sn	Ba
"A" or EM-197-F	Idle	----	----	----	----	tr[a]	1.80	0.37	----	----	----
		----	----	----	----	----	0.46	----	----	----	----
	1600 - 0%	1.35	----	----	----	----	0.84	----	----	----	----
	1600 - 25%	----	----	----	----	----	tr[a]	tr[a]	----	----	----
	1600 - 50%	tr[a]	----	----	----	tr[a]	2.07	0.38	----	----	----
		----	----	----	----	----	1.04	----	----	----	----
	1600 - 75%	----	----	----	----	----	1.60	----	----	----	----
	1600 - 100%	2.32	----	----	----	----	0.66	tr[a]	----	----	----
	2100 - 0%	----	----	----	----	----	1.06	tr[a]	----	----	----
	2100 - 25%	----	----	----	----	----	2.50	----	----	----	----
	2100 - 50%	1.28	----	----	----	----	0.50	tr[a]	----	----	----
	2100 - 75%	tr[a]	----	----	----	----	1.05	0.33	----	----	----
	2100 - 100%	2.41	----	----	----	tr[a]	0.70	----	----	----	----
	Composite	----	----	----	----	----	0.75	----	----	----	----
		----	----	tr[a]	----	0.12	0.23	----	----	----	----
"B" or EM-195-F	Idle	----	----	----	----	0.07	1.13	----	----	----	----
	1600 - 0%	----	----	----	----	----	0.46	----	----	----	----
	1600 - 50%	----	----	----	----	tr[a]	0.84	----	----	----	----
	2100 - 0%	----	----	----	----	0.09	0.53	----	----	----	----
	2100 - 50%	----	----	----	----	----	1.46	tr[a]	----	----	----
	2100 - 100%	----	----	----	----	----	0.58	----	----	----	----
"C" or EM-193-F	Idle	----	----	----	----	----	0.78	0.28	----	----	----
	1600 - 0%	----	----	----	----	----	0.33	----	----	----	----
	1600 - 50%	----	----	----	----	----	4.02	----	0.07	----	----
	1600 - 100%	2.09	----	----	----	----	2.40	----	----	----	----
	2100 - 0%	----	----	----	----	tr[a]	3.58	0.28	----	----	----
	2100 - 50%	----	----	----	----	0.07	0.74	----	----	----	----
	2100 - 100%	1.16	----	----	----	----	1.70	----	----	----	----
	Composite	----	----	----	----	----	0.50	----	----	----	----
"A+additive" or EM-209-F	Idle	tr[a]	----	----	----	----	0.23	----	----	----	----
	1600 - 0%	1.30	----	----	----	----	0.30	----	----	----	----
	1600 - 50%	----	----	----	----	0.07	1.04	0.48	----	----	----
	1600 - 100%	3.10	----	----	----	----	0.80	0.22	tr[a]	----	----
	2100 - 0%	----	----	----	----	----	0.75	----	----	----	----
	2100 - 50%	----	----	----	----	----	0.15	----	----	----	----
	2100 - 100%	1.13	----	----	----	----	0.35	----	----	----	----
	Composite	----	----	----	----	----	tr[a]	----	----	----	----
		----	----	----	----	----	----	----	----	----	----

[a] "trace" means an amount less than the minimum detectable limit but more than 2/3 of that limit

BLE F-1 (Cont'd). ANALYSIS FOR METALS IN PARTICULATE SAMPLES FROM TWO FUELS, DETROIT DIESEL 6L71-T ENGINE

Fuel	Operating condition	Metal analysis in $\mu g/cm^2$ on filter									
		Ca	V	Mn	Ni	Cu	Zn	Pb	Sr	Sn	Ba
+additive" EM-210-F	Idle	2.25	----	----	----	----	0.07	----	----	----	tr[a]
	1600- 0%	1.85	----	----	----	----	0.38	----	tr[a]	----	----
		1.66	----	----	----	----	0.47	tr[a]	----	----	2.66
	1600- 50%	33.28	0.21	----	----	----	0.29	0.23	0.12	----	4.79
	1600-100%	40.84	0.27	----	----	----	0.57	0.23	0.13	----	6.38
		30.55	0.14	----	----	----	0.24	0.25	0.09	----	3.72
	2100- 0%	11.41	----	----	----	----	0.20	----	0.05	----	tr[a]
	2100- 50%	25.66	----	----	----	----	0.45	----	0.11	----	2.82
	2100-100%	41.16	0.41	----	----	----	0.55	0.34	0.15	----	4.26
	Composite	23.49	----	----	----	----	0.45	0.19	0.10	----	4.26
		18.17	----	----	----	----	0.20	----	0.07	----	4.63
+additive" EM-211-F	Idle	3.70	----	----	----	----	0.19	----	tr[a]	----	----
	1600- 50%	16.08	----	----	----	----	1.40	tr[a]	0.07	----	3.30
	2100-100%	52.57	0.42	----	----	----	1.44	0.33	0.14	----	7.66
	Composite	23.79	----	----	----	----	0.46	tr[a]	0.09	----	4.49
		21.27	----	----	----	----	0.49	----	0.08	----	3.26

trace" means an amount less than the minimum detection limit
ut more than 2/3 of that limit

TABLE F-2. ANALYSIS FOR METALS IN PARTICULATE SAMPLES FROM FOUR FUELS, CUMMINS NTC-290 ENGINE

Fuel	Operating condition	Metal analysis in $\mu g/cm^2$ on filter									
		Ca	V	Mn	Ni	Cu	Zn	Pb	Sr	Sn	Ba
"A" or EM-197-F	Idle	----	----	----	----	----	----	----	----	----	----
	1500 - 0%	----	----	----	----	----	tr[a]	tr[a]	tr[a]	----	----
	1500 - 50%	----	----	----	----	----	1.89	0.22	tr[a]	----	----
	1500 - 100%	----	----	----	----	----	1.29	tr[a]	0.06	----	----
	2100 - 0%	0.65	----	----	----	----	tr[a]	0.21	----	----	----
	2100 - 50%	1.38	----	----	----	----	0.93	tr[a]	0.10	----	----
	2100 - 100%	1.61	----	----	----	----	1.06	----	----	----	----
	Composite	----	----	----	----	----	0.07	----	----	----	----
		1.53	----	----	----	----	0.05	0.04	0.06	----	----
"B" or EM-204-F	Idle	----	----	----	----	tr[a]	----	0.33	----	----	----
	1500 - 0%	----	----	----	----	----	----	tr[a]	----	----	----
	1500 - 25%	tr[a]	----	----	----	----	----	0.52	----	----	----
	1500 - 50%	----	----	----	----	----	----	0.47	----	----	----
	1500 - 75%	----	----	----	----	----	0.27	0.44	----	----	----
	1500 - 100%	----	----	----	----	tr[a]	0.10	0.44	----	----	----
	2100 - 0%	----	----	----	----	----	0.25	0.31	----	----	----
	2100 - 25%	----	----	----	----	----	tr[a]	0.36	----	----	----
	2100 - 50%	----	----	----	----	----	0.88	0.33	----	----	----
	2100 - 75%	----	----	----	----	tr[a]	0.13	0.72	----	----	----
	2100 - 100%	----	----	----	----	----	0.08	0.61	----	----	----
	Composite	----	----	----	----	----	0.10	tr[a]	----	----	----
		----	----	----	----	----	----	0.34	----	----	----
"C" or EM-198-F	Idle	----	----	----	----	----	----	----	0.07	----	----
	1500 - 0%	----	----	----	----	----	----	0.21	tr[a]	----	----
	1500 - 50%	----	----	----	----	----	0.07	0.29	tr[a]	----	----
	1500 - 100%	tr[a]	----	----	----	----	0.12	0.25	----	----	----
	2100 - 0%	----	----	tr[a]	----	----	0.07	0.52	0.08	----	----
	2100 - 50%	----	----	----	----	----	0.06	tr[a]	tr[a]	----	----
	2100 - 100%	tr[a]	----	----	----	----	0.20	----	0.06	----	----
	Composite	1.19	----	----	----	----	0.13	tr[a]	tr[a]	----	----
		----	----	----	----	----	0.34	----	----	----	----
"A+additive" or EM-209-F	Idle	----	----	----	----	----	----	----	----	----	----
	1500 - 0%	----	----	----	----	----	----	0.24	----	----	----
	1500 - 50%	----	----	----	----	----	----	----	----	----	----
	1500 - 100%	----	----	----	----	----	0.08	tr[a]	----	----	----
	2100 - 0%	----	----	----	----	0.10	tr[a]	----	tr[a]	----	----
	2100 - 50%	----	----	----	----	0.07	0.15	----	----	----	----
	2100 - 100%	tr[a]	----	----	----	----	0.22	----	tr[a]	----	----
	Composite	----	----	----	----	----	tr[a]	0.32	----	----	----
		----	----	----	----	----	0.12	0.30	----	----	----

[a] "Trace" means an amount less than the minimum detection limit, but more than 2/3 of that limit

TABLE F-2 (Cont'd). ANALYSIS FOR METALS IN PARTICULATE SAMPLES FROM TWO FUELS, CUMMINS NTC-290 ENGINE

Fuel	Operating condition	Metal analysis in $\mu g/cm^2$ on filter									
		Ca	V	Mn	Ni	Cu	Zn	Pb	Sr	Sn	Ba
"B+additive" or EM-224-F	Idle	8.13	----	tr[a]	----	0.12	0.28	----	0.07	----	1.35
	1500 - 0%	12.13	----	0.26	----	0.11	0.17	0.29	0.07	----	2.31
	1500 - 50%	40.56	----	----	----	0.12	0.37	0.34	0.13	----	6.74
	1500 - 100%	45.19	----	----	----	tr[a]	0.20	0.31	0.15	----	7.58
	2100 - 0%	14.92	----	----	----	0.12	0.46	tr[a]	0.07	----	2.61
	2100 - 50%	30.51	----	tr[a]	----	0.17	0.53	0.27	0.14	----	4.81
	2100 - 100%	38.07	----	----	----	0.14	0.10	tr[a]	0.14	----	5.49
	Composite	9.06	----	tr[a]	----	0.16	0.43	----	0.07	----	tr[a]
		22.49	----	0.28	----	0.18	0.47	0.42	0.11	----	4.11
"C+additive" or EM-211-F	Idle	8.89	----	tr[a]	----	0.11	tr[a]	----	0.05	----	1.42
	1500 - 0%	11.29	----	----	----	0.12	0.40	----	tr[a]	----	2.16
	1500 - 50%	44.16	----	----	----	0.12	0.37	0.26	0.15	----	7.46
	1500 - 100%	35.79	----	----	----	0.17	0.31	----	0.18	----	4.91
	2100 - 0%	18.94	----	----	----	0.18	0.25	0.28	0.08	----	3.65
	2100 - 50%	3.86	----	tr[a]	----	0.18	0.32	----	0.12	----	7.18
	2100 - 100%	58.58	----	----	----	0.11	0.19	----	0.19	----	8.94
	Composite	30.58	----	----	----	0.15	0.13	----	0.14	----	5.50
		31.98	----	----	----	0.15	0.18	tr[a]	0.17	----	5.51

[a] "Trace" means an amount less than the minimum detection limit, but more than 2/3 of that limit

APPENDIX G

SUMMARY OF BaP RESULTS

TABLE G-1. SUMMARY OF BaP RESULTS, DETROIT DIESEL 6L-71T ENGINE

Fuel	Engine rpm and load	mg/hr						$\mu g/m^3$					
		1	2	3	4	5	Avg.	1	2	3	4	5	Avg.
B	Idle	0.139	2.77				1.45	0.739	12.8				6.77
	1600 - 0	28.5					28.5	36.4					36.4
	1600 - 50	4.17					4.17	4.81					4.81
	2100 - 100	9.92	35.0				22.5	6.23	21.9				14.1
	Composite	10.3	15.2	15.4	5.98	4.00	10.2	9.68	14.0	14.2	5.40	3.50	9.36
C	Idle	0.135	2.86	8.32			3.77	0.755	16.2	38.3			18.4
	1600 - 0	11.1					11.1	14.7					14.7
	1600 - 50	3.02	10.2	1.44			4.89	3.37	11.2	1.56			5.38
	1600 - 75	14.1					14.1	14.0					14.0
	1600 - 100	7.94					7.94	7.09					7.09
	2100 - 0	37.1					37.1	33.6					33.6
	2100 - 25	16.5					16.5	14.4					14.4
	2100 - 50	26.6					26.6	20.1					20.1
	2100 - 75	22.4					22.4	16.0					16.0
	2100 - 100	0.823					0.823	0.512					0.512
	Composite	3.52	0.545	65.3			23.1	3.30	0.510	61.8			21.9
A	Idle	0.165					0.165	0.898					0.898
	1600 - 50	1.62					1.62	1.79					1.79
	1600 - 100	9.93					9.93	8.96					8.96
	Composite	2.28	3.56				2.92	2.11	3.29				2.70
B+	Composite	14.4	23.0				18.7	12.9	20.7				16.8
C+	Composite	16.0	11.2				13.6	14.5	10.0				12.2
A+	Idle	1.13					1.13	5.29					5.29
	1600 - 50	13.5					13.5	14.7					14.7
	Composite	16.2	3.18				9.69	14.8	2.91				8.86

TABLE G-2. SUMMARY OF BaP RESULTS, CUMMINS NTC-290 ENGINE

Engine rpm and load	Fuel	mg/hr			$\mu g/m^3$			Fuel	mg/hr			$\mu g/m^3$		
		1	2	Avg.	1	2	Avg.		1	2	Avg.	1	2	Avg.
Idle	B	0.55	-----	0.55	2.48	-----	2.48	B+	1.43	----	1.43	6.42	----	6.42
1500 - 0		2.75	-----	2.75	5.29	-----	5.29		2.98	----	2.98	5.63	----	5.63
1500 - 50		<0.29	-----	<0.3	<0.48	-----	<0.5		3.86	----	3.86	6.35	----	6.35
1500 - 100		1.13	0.73	0.93	1.54	0.97	1.25		7.33	----	7.33	9.83	----	9.83
2100 - 0		4.49	-----	4.49	6.37	-----	6.37		19.4	----	19.4	26.8	----	26.8
2100 - 50		2.17	-----	2.17	2.47	-----	2.47		6.36	----	6.36	7.14	----	7.14
2100 - 100		2.53	-----	2.53	2.32	-----	2.32		5.51**	----	5.51	5.03**	----	5.03
Composite		4.04	-----	4.04	5.66	-----	5.66		7.71	9.66	8.68	10.7	13.3	12.0
Idle	A	0.40	-----	0.40	1.73	-----	1.73	A+	<0.13	----	<0.1	<0.55	----	<0.5
1500 - 0		1.72	-----	1.72	3.24	-----	3.24		2.07	----	2.07	3.83	----	3.83
1500 - 50		1.01	-----	1.01	1.65	-----	1.65		*	----	*	*	----	*
1500 - 100		1.08	-----	1.08	1.46	-----	1.46		*	----	*	*	----	*
2100 - 0		1.94	-----	1.94	2.71	-----	2.71		*	----	*	*	----	*
2100 - 50		5.82	-----	5.82	6.68	-----	6.68		3.62	----	3.62	4.15	----	4.15
2100 - 100		4.44	-----	4.44	4.01	-----	4.01		*	----	*	*	----	*
Composite		2.12	<0.61	1.06 to 1.36	2.87	<0.85	1.44 to 1.86		*	1.54	~0.08	*	2.11	~1.0
Idle	C	0.49	-----	0.49	2.1	-----	2.1	C+	1.21	----	1.21	5.60	----	5.60
1500 - 0		2.82	-----	2.82	5.24	-----	5.24		6.53	----	6.53	12.2	----	12.2
1500 - 50		<0.26	-----	<0.3	<0.43	-----	<0.4		3.08	----	3.08	4.93	----	4.93
1500 - 100		0.76	-----	0.76	1.00	-----	1.00		6.31	----	6.31	8.15	----	8.15
2100 - 0		0.87	-----	0.87	1.20	-----	1.20		5.75	----	5.75	7.87	----	7.87
2100 - 50		2.47	-----	2.47	2.70	-----	2.70		11.6	----	11.6	12.9	----	12.9
2100 - 100		1.77	-----	1.77	1.57	-----	1.57		13.5	----	13.5	9.99	----	9.99
Composite		5.94	*	~3.0	8.03	*	~4.0		7.07	12.1	9.58	9.59	15.9	12.8

* Not enough to measure

** Small amount of solubles

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

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16. ABSTRACT

To develop a methodology for characterizing particulate emissions from diesel engines, one 2-stroke cycle engine and one 4-stroke cycle engine were operated in both individual steady-state modes and according to a variation of the 13-mode diesel emissions measurement procedure. Both engines were operated on three fuel types, each of which was used with one of two available diesel fuel additives as well as by itself.

The primary particulate sampling technique employed was a dilution tunnel; and secondary evaluation techniques included a diluter-sampler developed under contract to EPA by another organization, a light extinction smokemeter, and a filter-type sampling smokemeter. Gaseous emissions were also measured, providing a running check on engine conditon.

Particulate mass rates were calculated from gravimetric data; and analysis of particulate included determination of sulfur, carbon, hydrogen, nitrogen, phenols, nitrosamines, trace metals, and organic solubles. Analysis of the organic soluble fraction included NMR, IR, paraffin boiling point distribution, benz(a)-pyrene, sulfur, carbon, hydrogen, nitrogen, and oxygen.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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